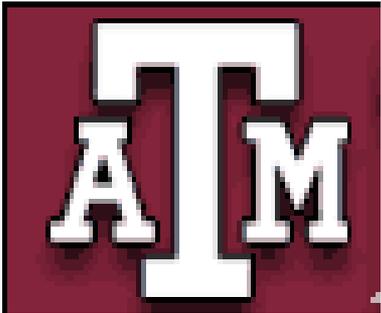


Nonperturbative Heavy Flavor Transport in Medium

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UU workshop, the Netherlands, Nov.14-17, 2012

Outline

1. Introduction:

- Heavy quark probe for hot & dense matter

2. HQ probe: a strongly coupled framework

- Transport coefficient
- HQ diffusion in QGP: Langevin + hydro simulation
- Hadronization: **coalescence** vs fragmentation
- D-meson diffusion in **hadronic phase**

3. Heavy ion phenomenology

- RHIC: Non-photonic electrons, **Ds vs D mesons**
- LHC: D,B mesons, non-photonic electrons

4. Summary

1.1 Introduction: HQ probe

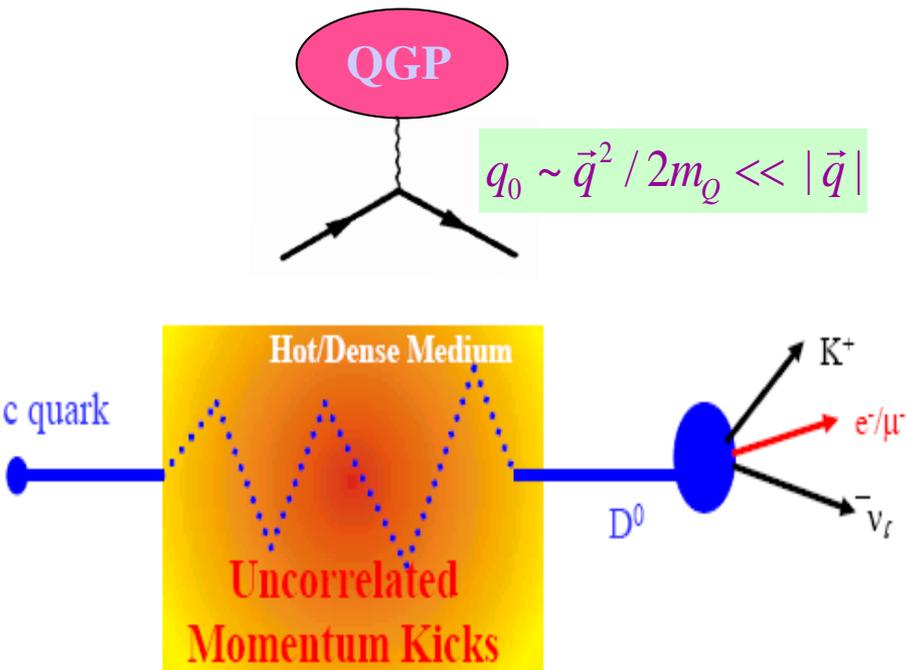
◆ primordial hard production + number conserved

◆ thermalization delayed

$$\tau_Q \approx \frac{m_Q}{T} \tau_q \approx 6 * \tau_q \geq \tau_{QGP}$$

→ Heavy quarks make a direct probe of the medium

◆ HQ diffusion in QGP: elastic scatterings with medium



**Brownian motion:
Fokker-Planck Equation**

$$\frac{\partial f}{\partial t} = \gamma \frac{\partial (pf)}{\partial p} + D \frac{\partial^2 f}{\partial p^2}$$

thermalization rate

diffusion coefficient

$$\gamma \propto \int |T_{Qq}|^2 (1 - \cos \theta) f^q$$

$$D = \gamma m_Q T$$

1.2 Comparing various models

Model	HQ trans. coeffi.	med. evolution	hadronization
Nantes	effective LO-pQCD	Heinz vs EPOS ideal hydro	coalescence+fragmentation
Turin	HTL	Romatschke viscous vs Heinz ideal hydro	fragmentation
Frankfurt	effective LO-pQCD	BAMPS full transport	fragmentation
Duke	$D_s = 6/(2\pi T)$	Heinz viscous hydro	fragmentation
LANL	meson dissociation	Bjorken expansion	med.-modified fragmentation

References: Gossiaux et al., 08,09,12; Alberico et al., 11,12; Uphoff et al., 11,12;
Cao et al., 11,QM12; Vitev et al.,07,09

◆ To account for radiative energy loss?

Frankfurt: K-factor

Nantes: K-factor + rad.

Duke: modified Langevin

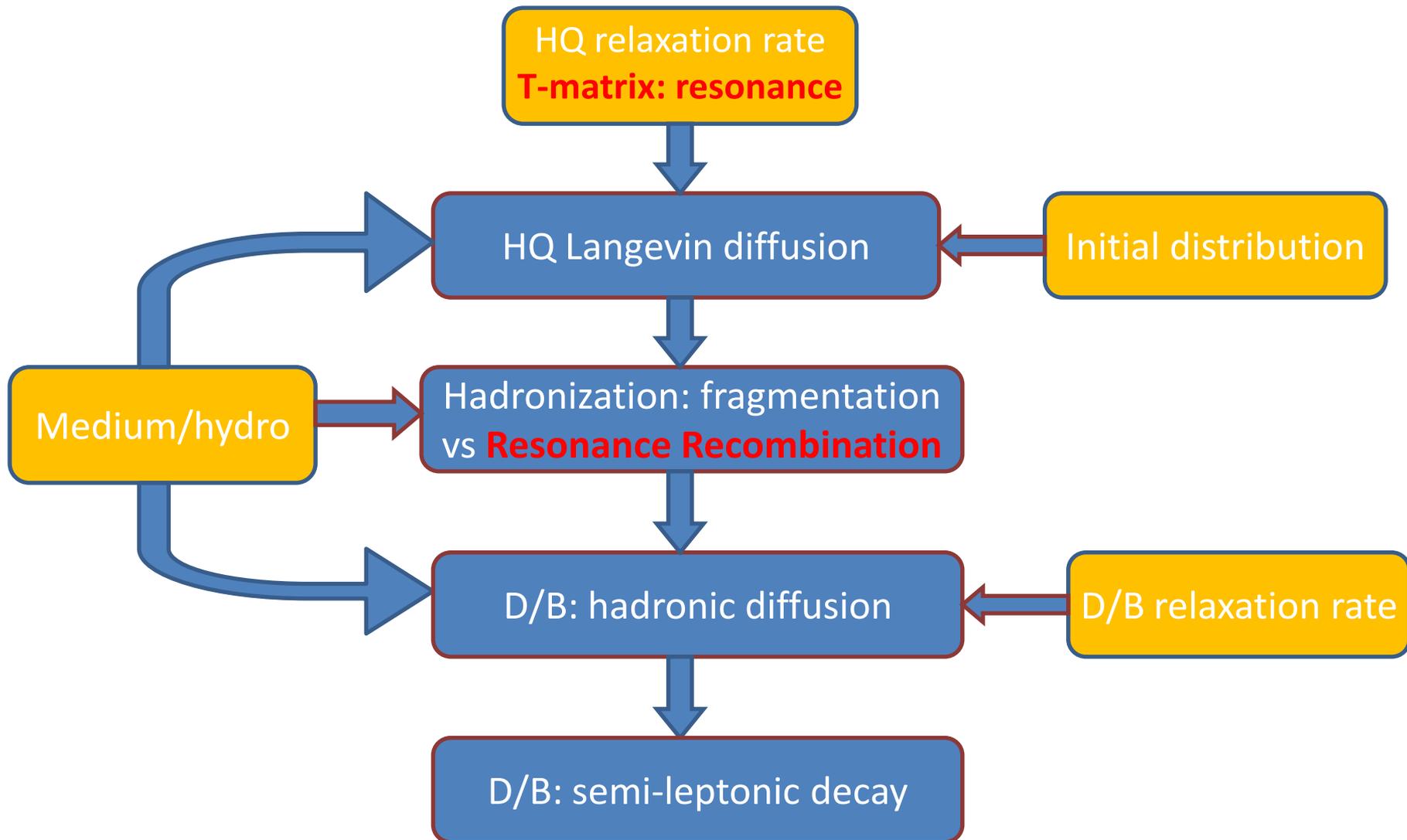
$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g$$

Violate detailed
balance

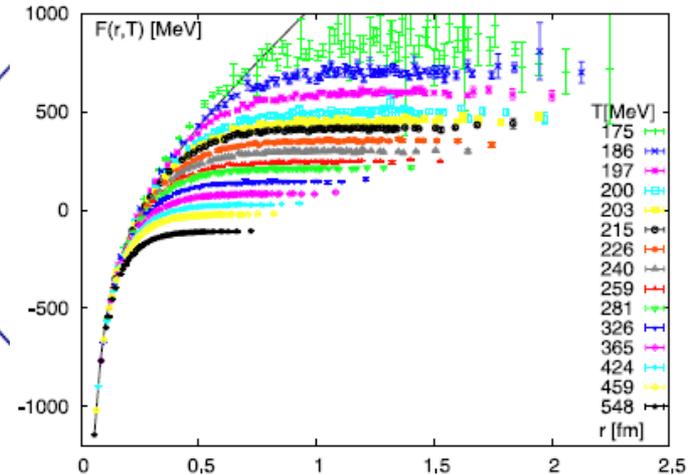
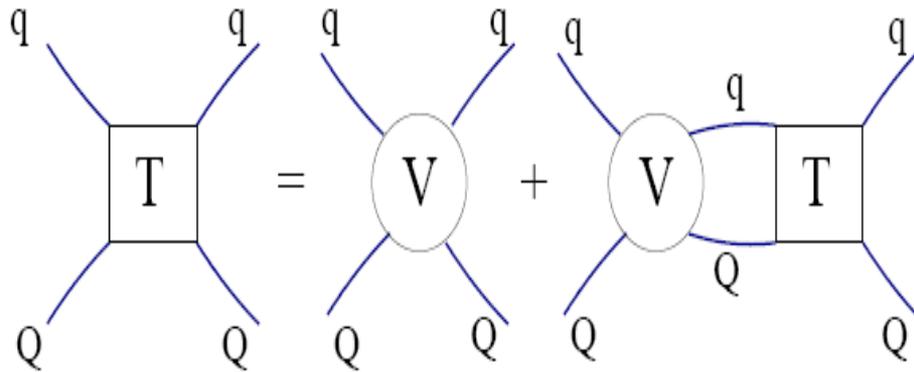
◆ To set benchmark for collisional energy loss

➔ **TAMU view: full non-perturbative (strongly coupled) approach**

1.3 A strongly coupled framework: HQ



2.1.1 HQ relaxation rate: T-matrix

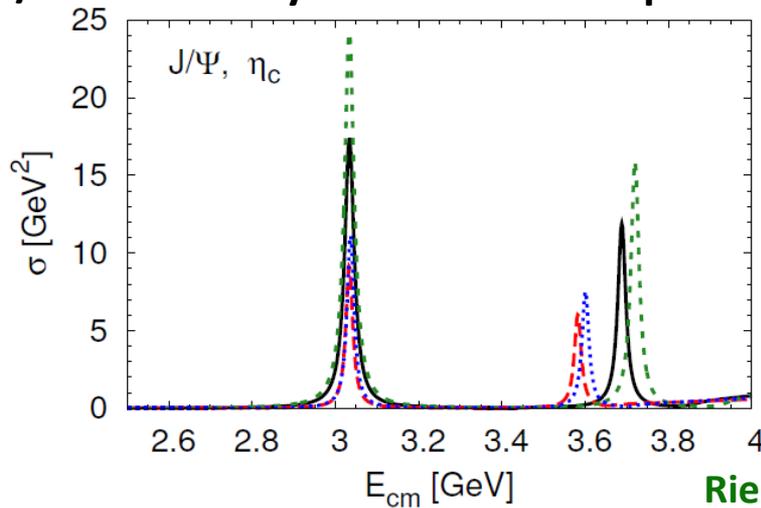


◆ lattice potential: **Kaczmarek, 2008**

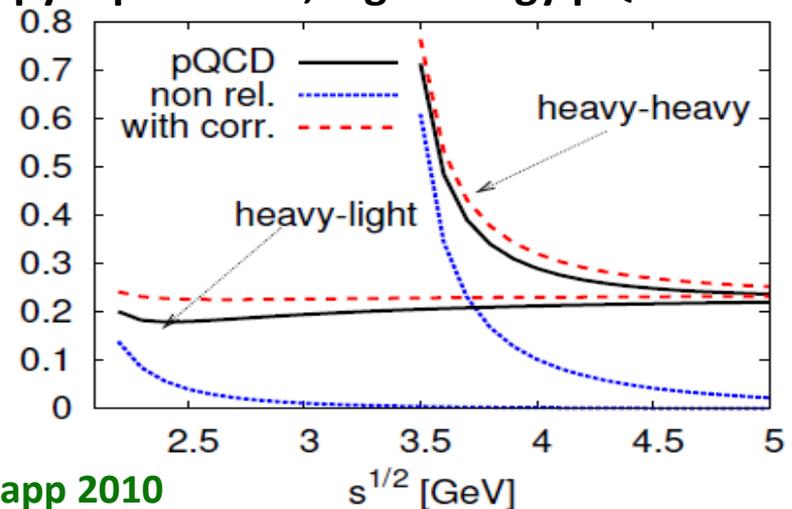
$$U = F - T \frac{\partial F}{\partial T}$$

➔ **Resummation & Unitarization**

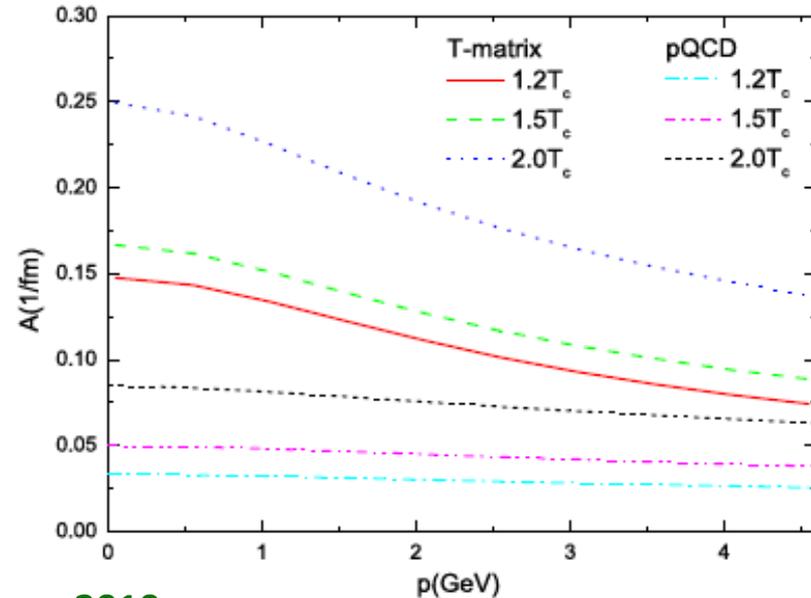
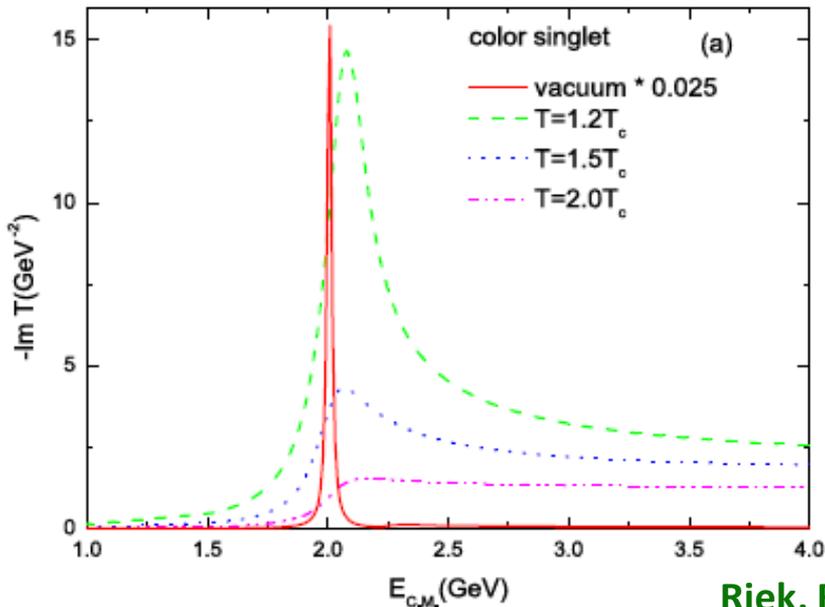
◆ Open/hidden heavy flavor: vacuum spectroscopy reproduced; high energy pQCD recovered



Riek, Rapp 2010



2.1.2 HQ relaxation rate: QGP



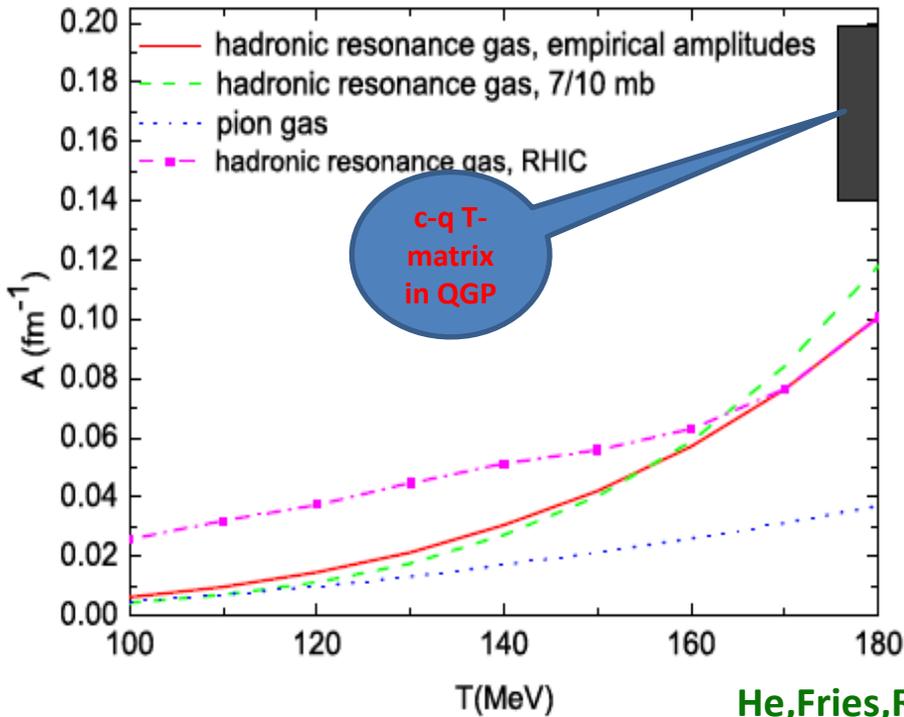
Riek, Rapp 2010

- ◆ T-matrix **resummation** → color singlet and anti-triplet broad **Feshbach resonances** up to $\sim 1.5 T_c$
- ◆ this **resonance correlation** → **resonance recombination**
- ◆ Recent update: T-matrix calculation of HQ-gluon scattering [Huggins,Rapp: 1206.6537] → $\sim 25\%$ enhancement of the full relaxation rate at low momentum

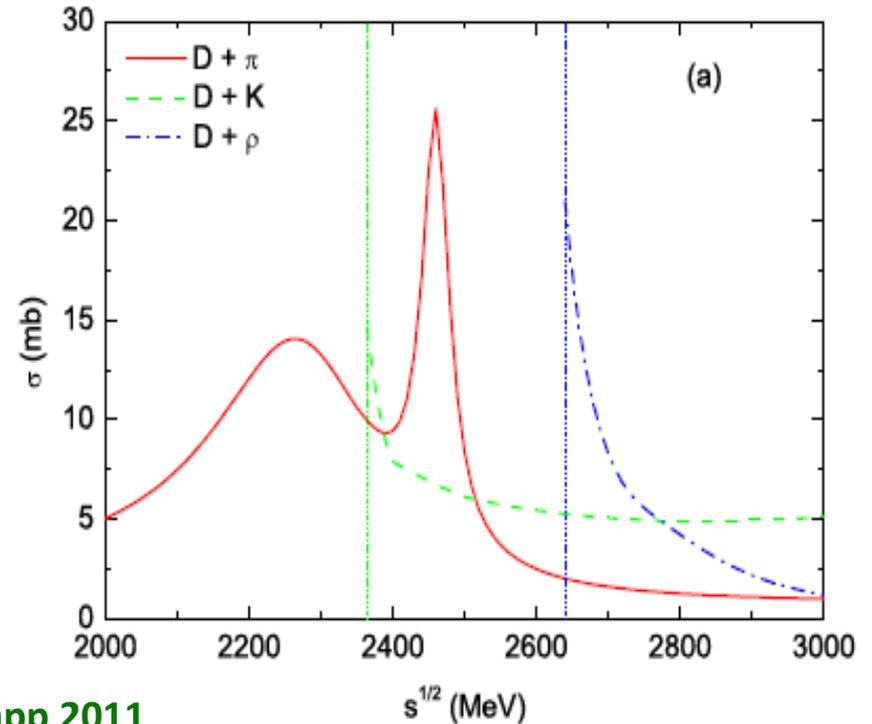
- ◆ T-matrix relaxation rate: a factor $\sim 4-5$ larger than LO pQCD at $T=1.2 T_c$
- ◆ T-dependence: **screening potential**;
p-dependence: less contribution from **Feshbach resonance** as p increases

2.1.3 D-meson relaxation rate : HRG

- ◆ D + pion, K,eta,rho,omega,K*,N,Delta, empirical s-wave cross sections from effective hadronic theory: Lutz et al., 2004,2006; E.Oset et al. 2007



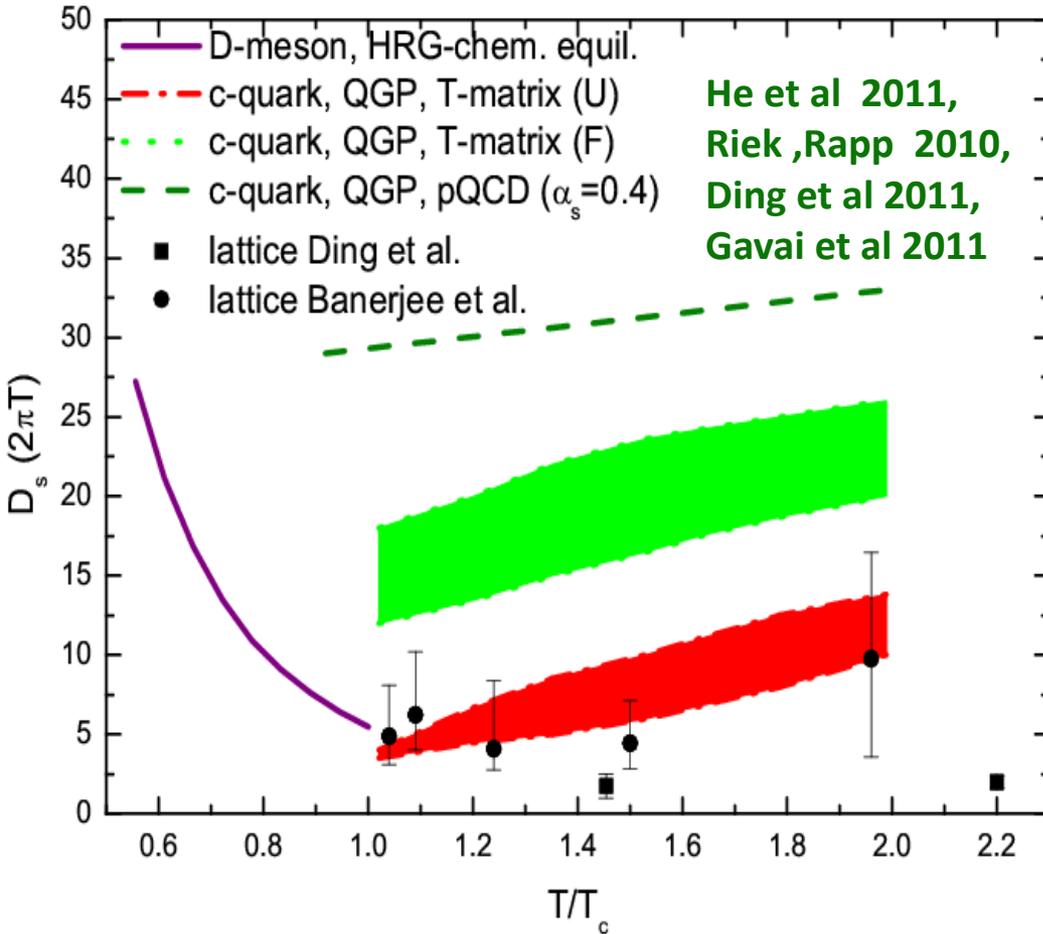
He,Fries,Rapp 2011



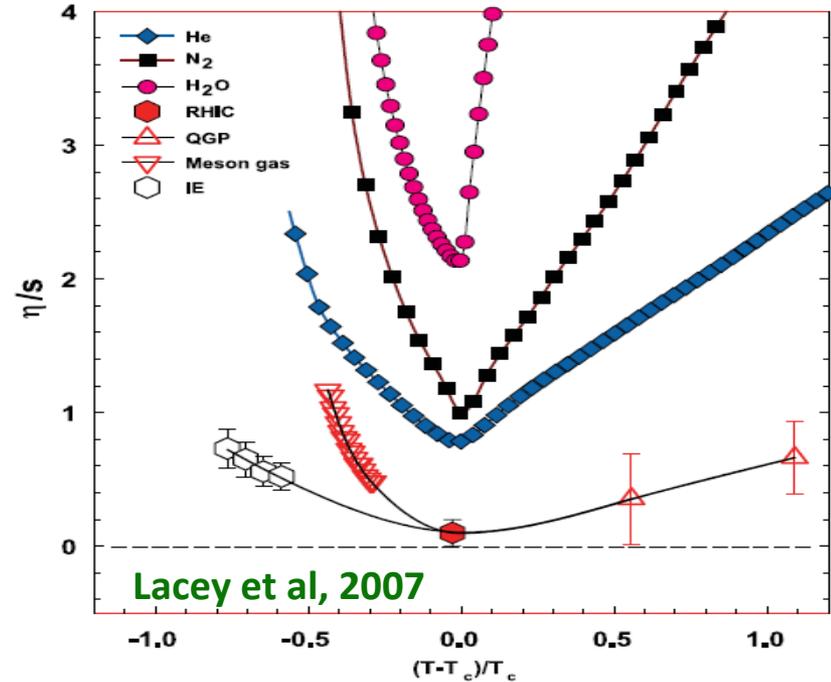
- ◆ $A \sim 0.1$ /fm at $T=180$ MeV, comparable to the non-perturbative T-matrix calculation of charm quark thermal relaxation rate in QGP

2.1.4 Summarizing charm diffusion coeffi.

Hadronic Matter vs. QGP vs. Lattice QCD (quenched)



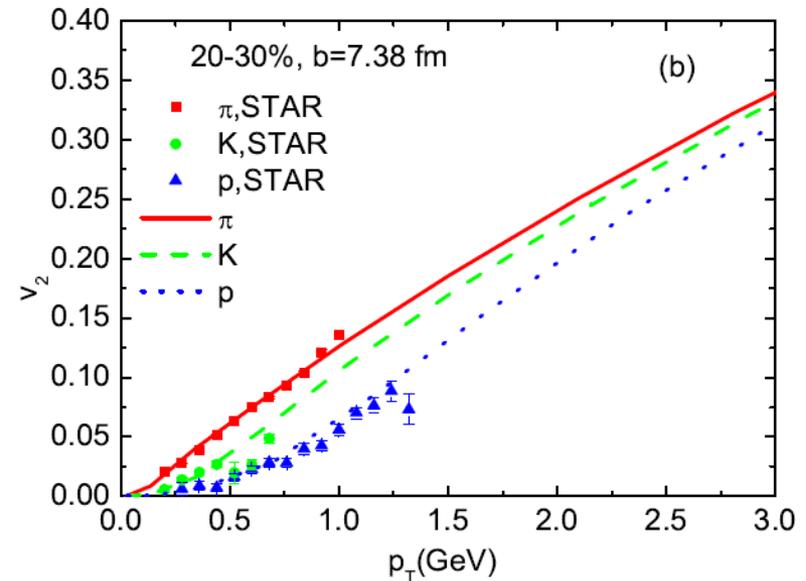
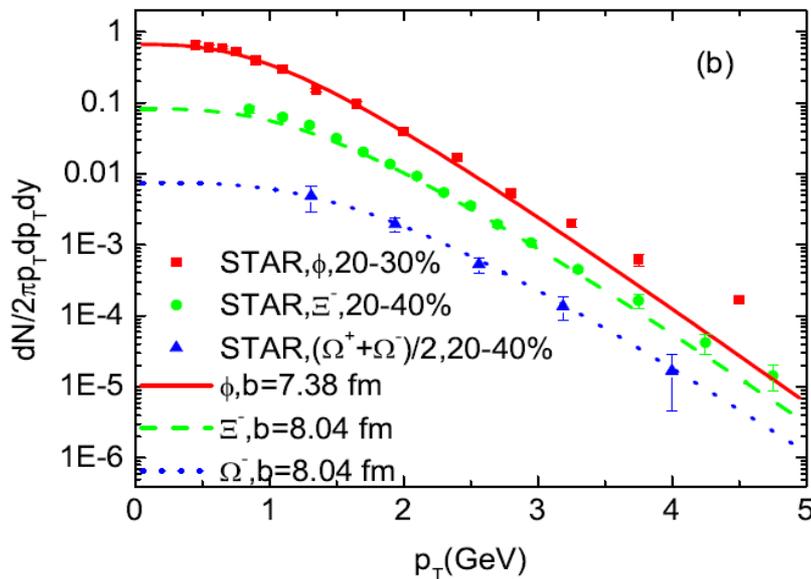
- ◆ Transport coeffi.: $\eta/s = (1/5 \sim 1/2)D_s T$, Danielewicz & Gyulassy, 1985
- ◆ D_s translates into $\eta/s = (2-5)/4\pi$ at $T=180$ MeV



- ◆ $D_s = T/(m_A)$: T-matrix vs lattice; Minimum around T_c + Quark-hadron duality?!
- ◆ The charm diffusion: another perspective of looking into the transport properties of sQGP/dense matter

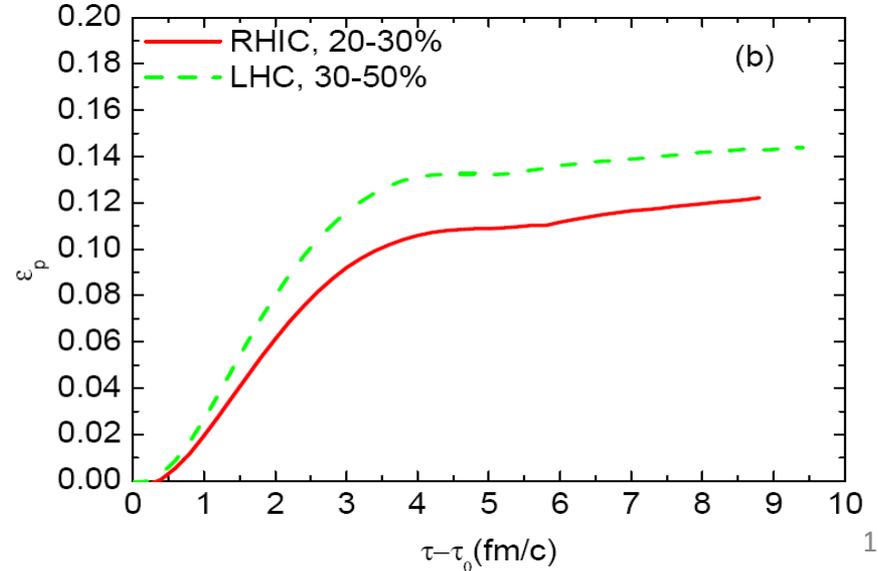
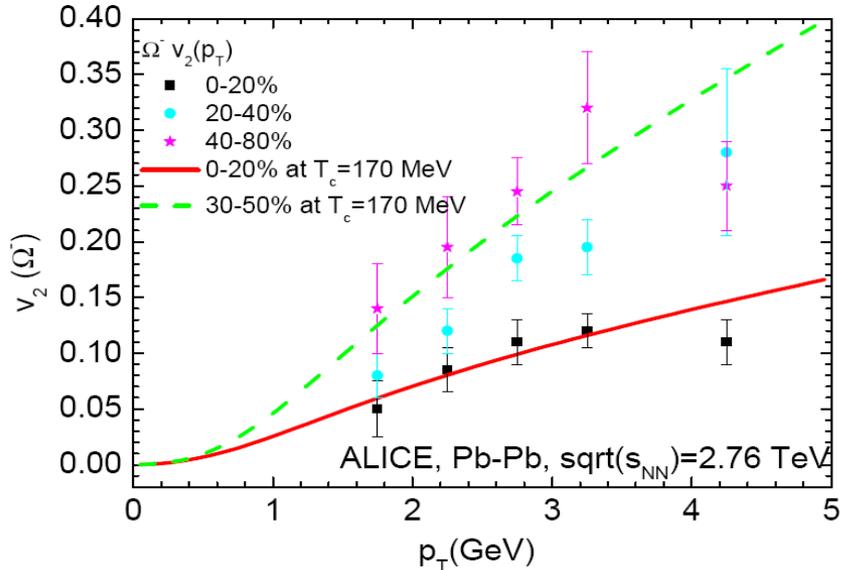
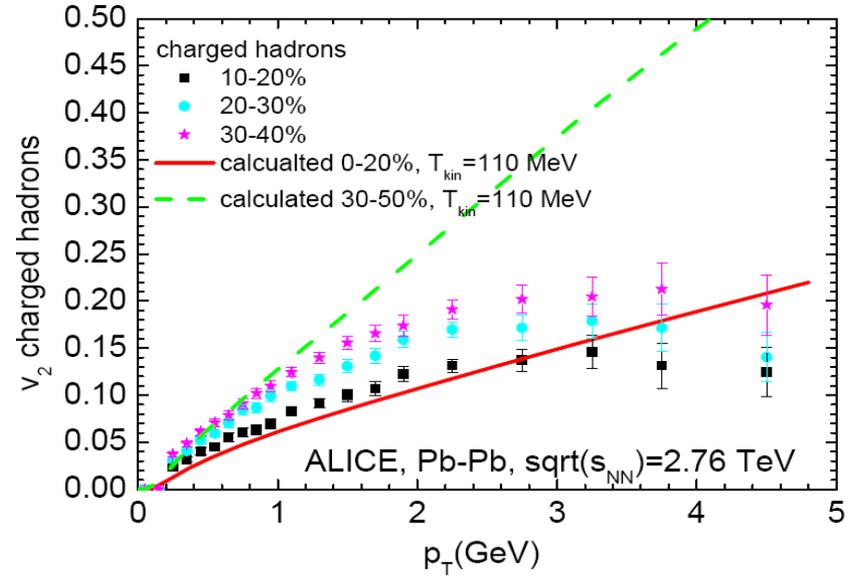
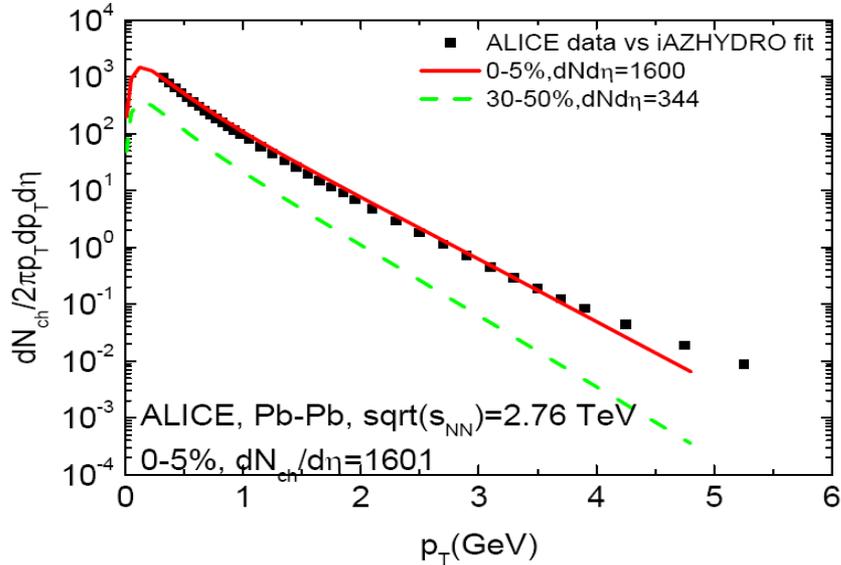
2.2.1 Medium evolution: hydro RHIC

- ◆ updated ideal 2+1 D hydro based on AZHYDRO **Kolb + Heinz, 2003**
- ◆ lattice/HRG-PCE EoS + pre-equilibrium flow + compact initial density $s(x,y) \sim n_{BC}(x,y)$
 → fast build-up of radial flow + essential saturation of bulk v_2 around T_c



- ◆ multistrange hadrons ϕ, Ξ, Ω probably freeze out earlier **STAR, PRC79,2009**
- ◆ multi-strange particles' spectra and v_2 fitted at $T_{ch} = 160$ MeV
 bulk particles' spectra and v_2 fitted at $T_{kin} = 110$ MeV **He, Fries, Rapp, 2012**

2.2.2 Medium evolution: hydro LHC

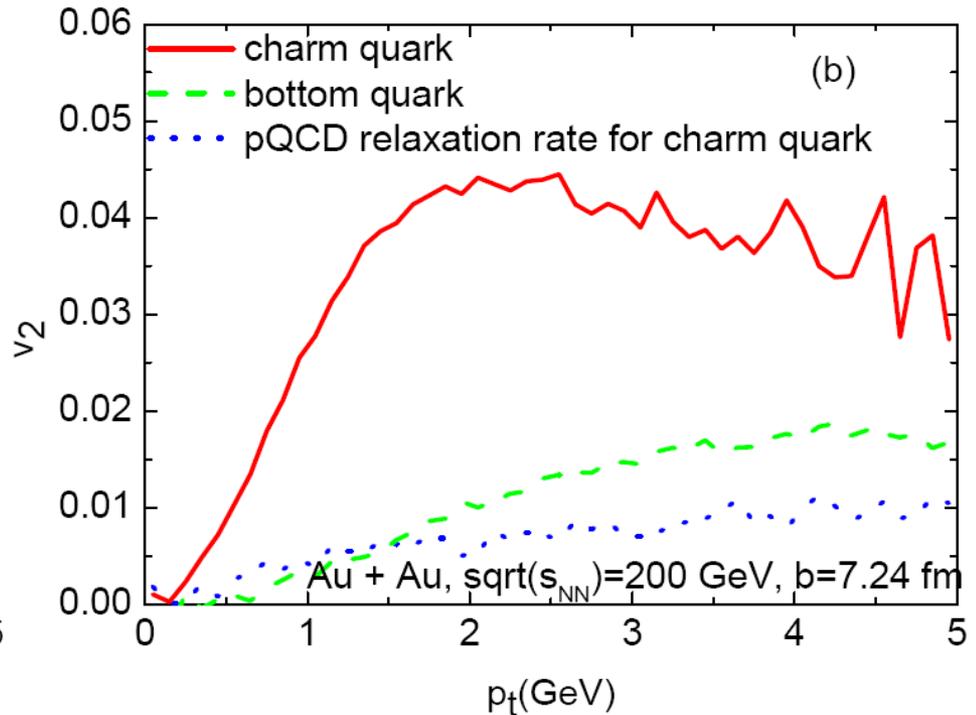
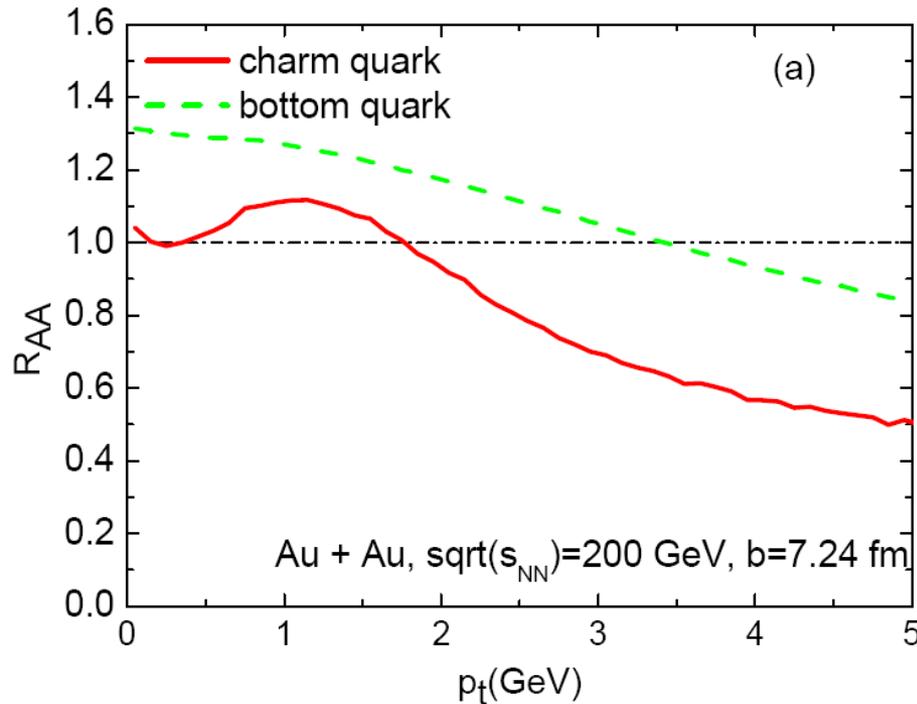


2.2.3 HQ diffusion: Langevin simulation

Langevin + hydro simulation down to $T_c=170$ MeV
 fluid rest frame updates \rightarrow boost to lab frame

$$dx = \frac{\mathbf{p}}{E} dt,$$

$$d\mathbf{p} = -\Gamma(p)\mathbf{p}dt + \sqrt{2D(\mathbf{p} + d\mathbf{p})} dt\rho$$



- ◆ initial HQ distribution: PYTHIA pp + Glauber n_{BC}
- ◆ quenching: early stage when medium particles' density is high
- ◆ v_2 : develops at later stage when the medium particles' v_2 is large

2.3.1 Hadronization: Resonance

Recombination

◆ Hadronization = Resonance formation $c\bar{q} \rightarrow D$

→ consistent with T-matrix findings of resonance correlations towards T_c

◆ Realized by Boltzmann equation Ravagli & Rapp, 2007

$$p^\mu \partial_\mu f_M(t, \vec{x}, \vec{p}) = -m\Gamma f_M(t, \vec{x}, \vec{p}) + p^0 \beta(\vec{x}, \vec{p})$$

$$\beta(\vec{x}, \vec{p}) = \int \frac{d^3 p_1 d^3 p_2}{(2\pi)^6} f_q(\vec{x}, \vec{p}_1) f_{\bar{q}}(\vec{x}, \vec{p}_2) \times \sigma(s) v_{\text{rel}}(\vec{p}_1, \vec{p}_2) \delta^3(\vec{p} - \vec{p}_1 - \vec{p}_2)$$

gain term

Breit-Wigner

$$\sigma(s) = g_\sigma \frac{4\pi}{k^2} \frac{(\Gamma m)^2}{(s - m^2) + (\Gamma m)^2}$$

◆ Equilibrium limit $f_M^{\text{eq}}(\vec{p}) = \frac{E_M(\vec{p})}{m\Gamma} \int d^3 x \beta(\vec{x}, \vec{p})$

◆ Energy conservation + detailed balance



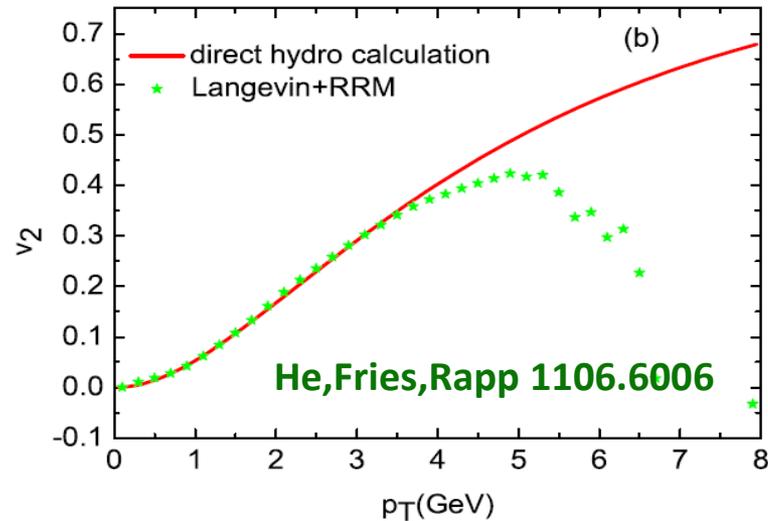
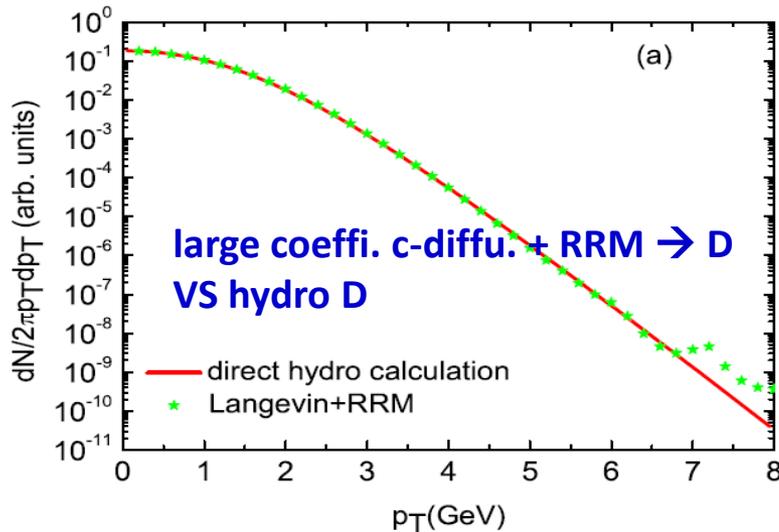
equilibrium mapping

2.3.2 Hadronization: coal. vs frag.

● RRM coalescence:

--- 4-mom. conservation, correct thermal equilibrium limit

--- implement on hydro freezeout hypersurface with full space-mom. correl.



● Diffusion vs coalescence: conceptually consistent

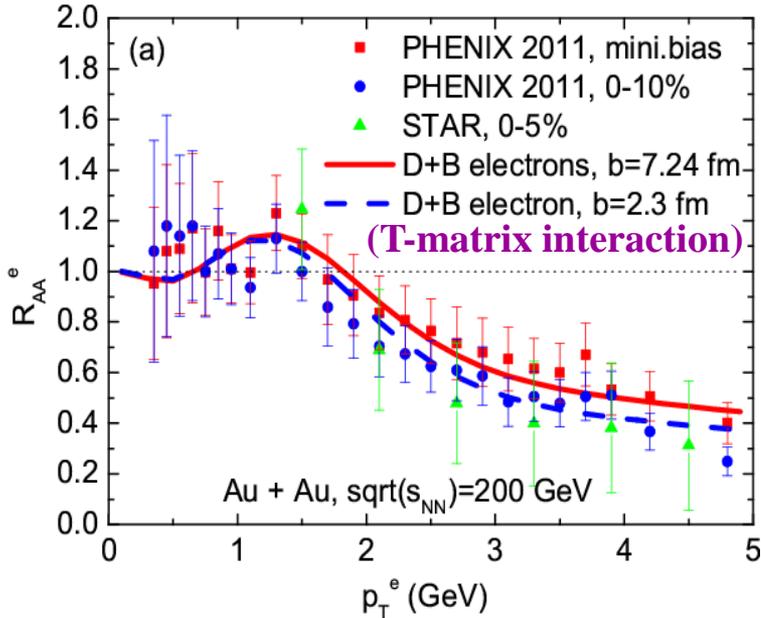
--- same interaction (T-matrix) underlying diffusion + hadronization

● Fragmentation: $D(z) = \delta(z-1)$ incompatible with thermalization

--- coal.proba. based on scattering rate: $P_{coal}(p_t) = \tau_{res} \gamma_Q(p_t)$

--- coal. dominates at low p_T ; yields to frag. at higher p_T

3.1 Phenomenology: e^\pm Spectra RHIC



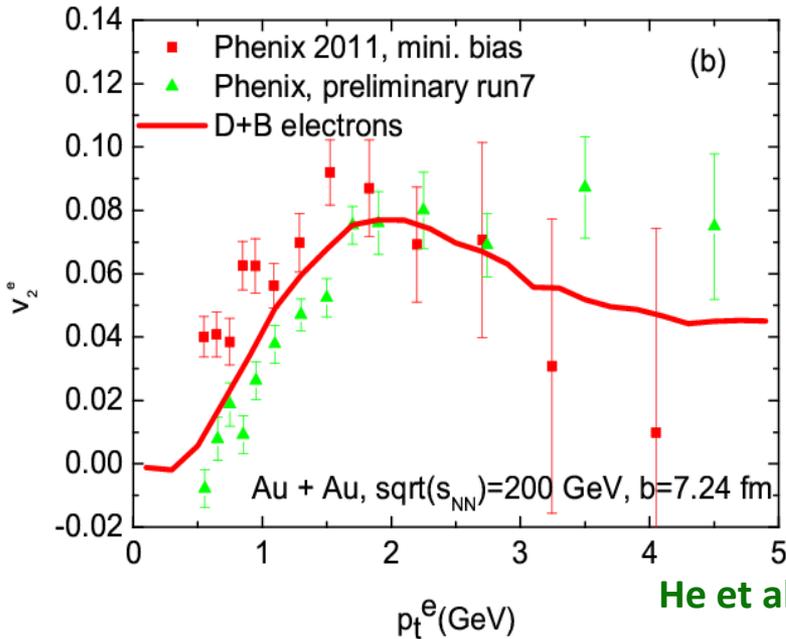
● medium modified D and B mesons: c/b diffusion + coal./frag. + hadronic diffusion

● semi-leptonic decays $c(b) \rightarrow s(c) + e + \nu$

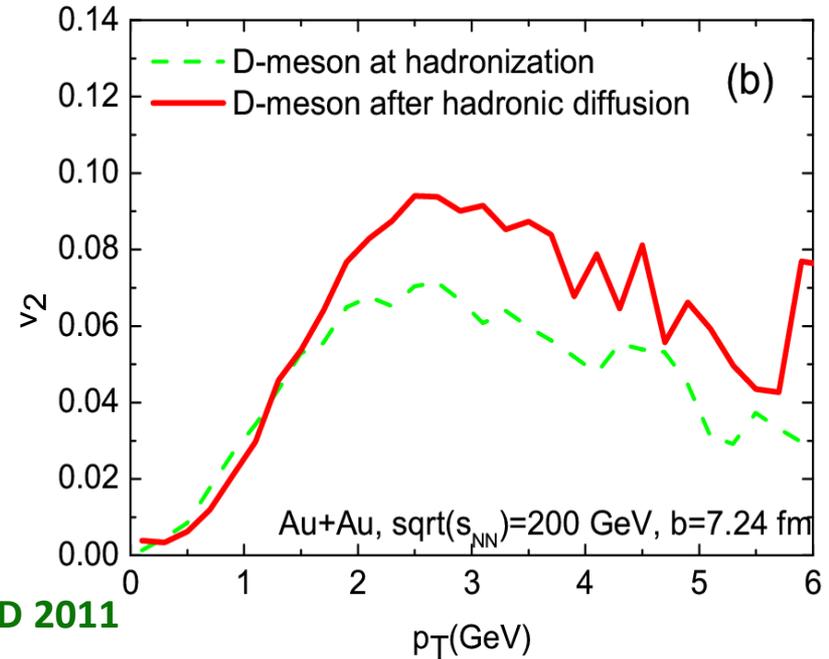
$$\langle |\mathcal{M}|^2 \rangle \propto (p_s \cdot p_\nu)(p_c \cdot p_e)$$

$$\langle |\mathcal{M}|^2 \rangle \propto (p_c \cdot p_e)(p_b \cdot p_\nu)$$

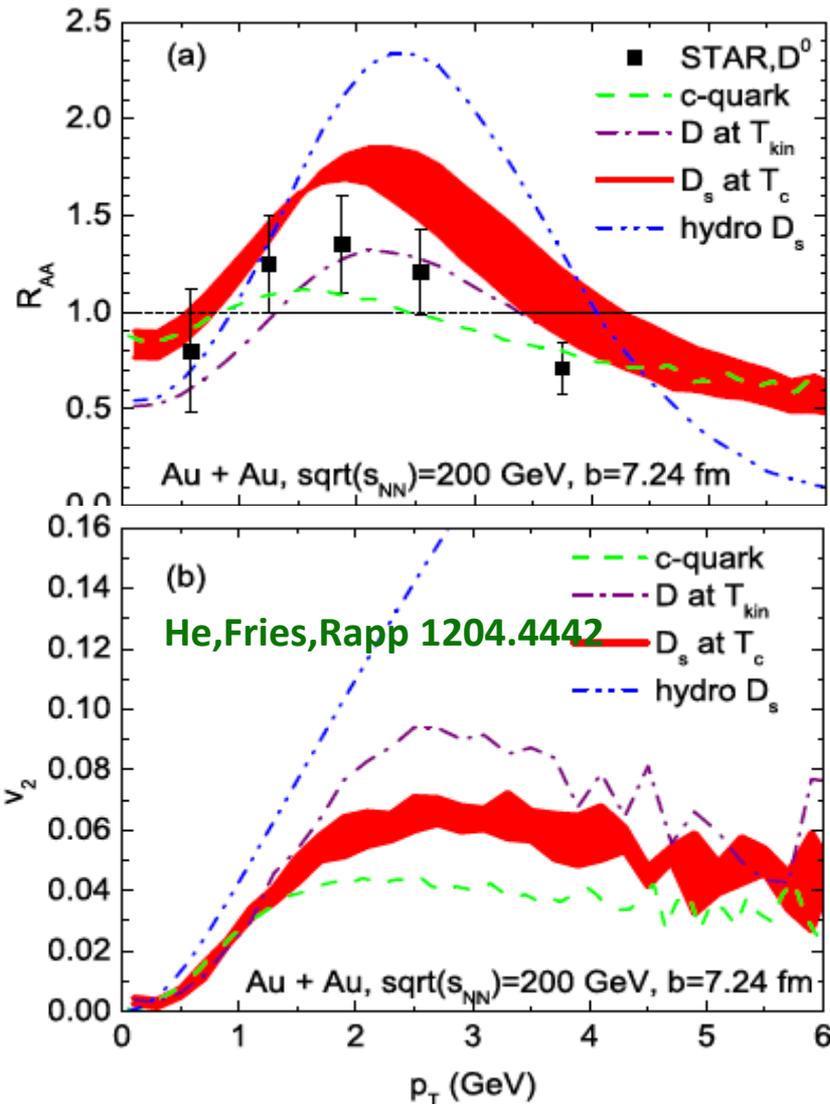
D Hadronic Diffusion



He et al., CPOD 2011

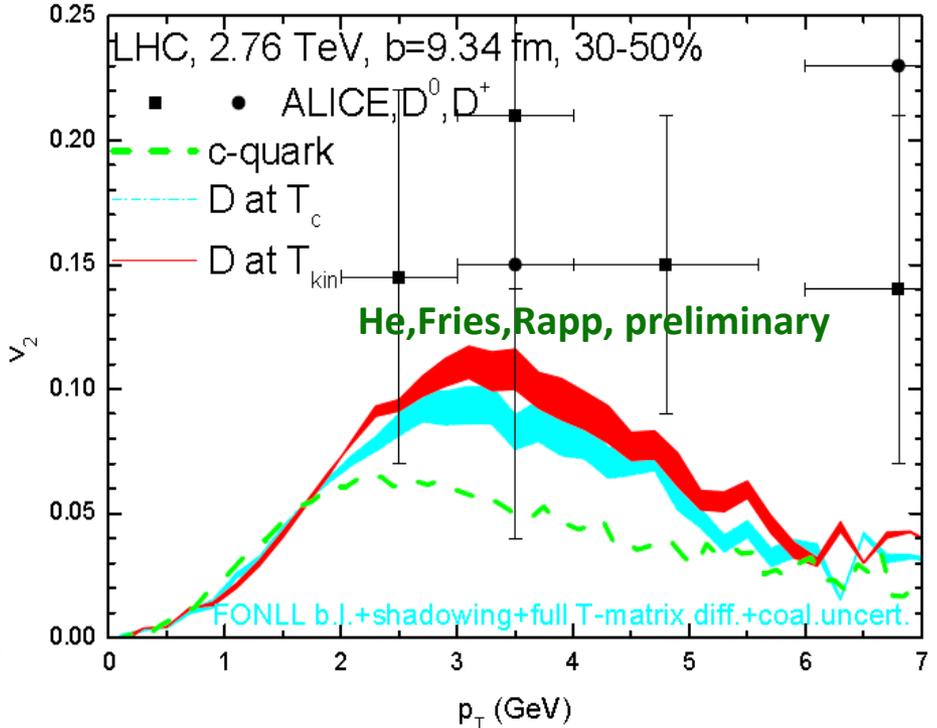
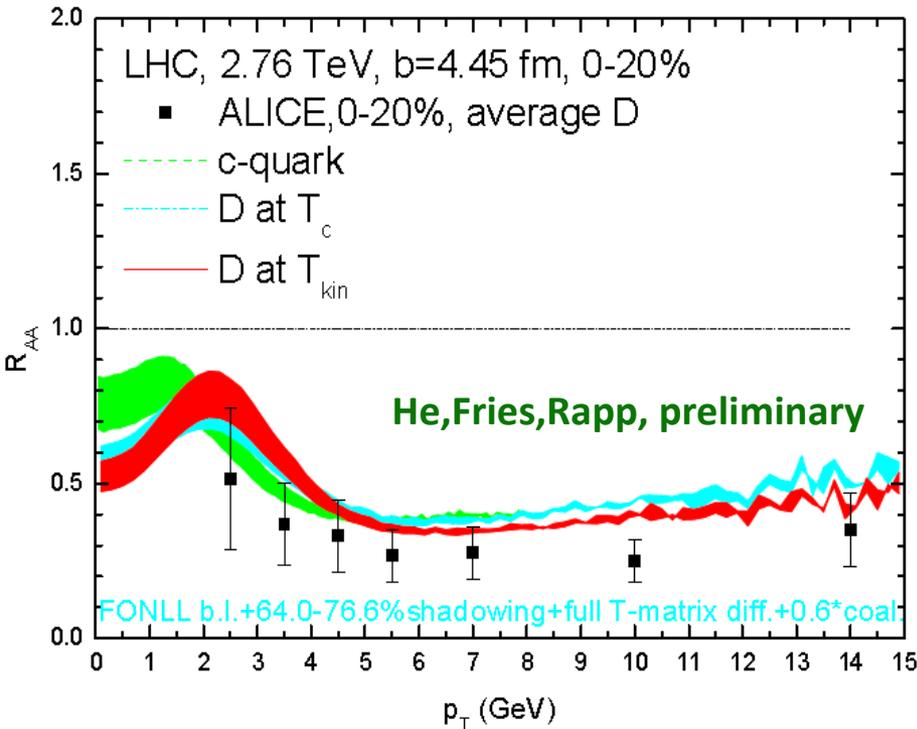


3.2 Phenomenology : D vs Ds mesons RHIC



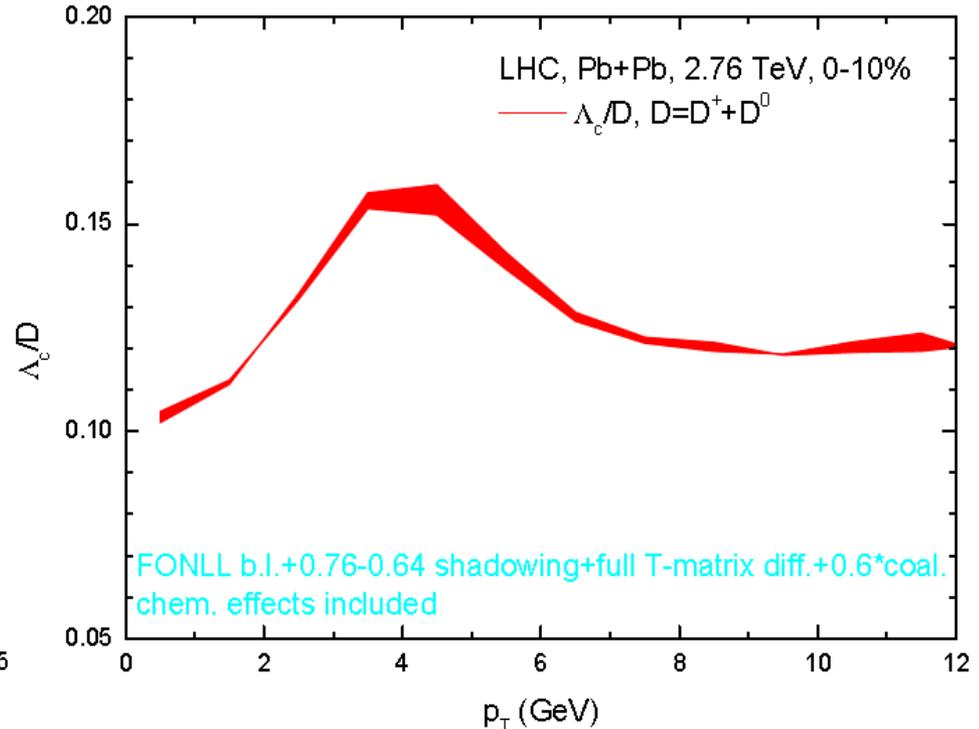
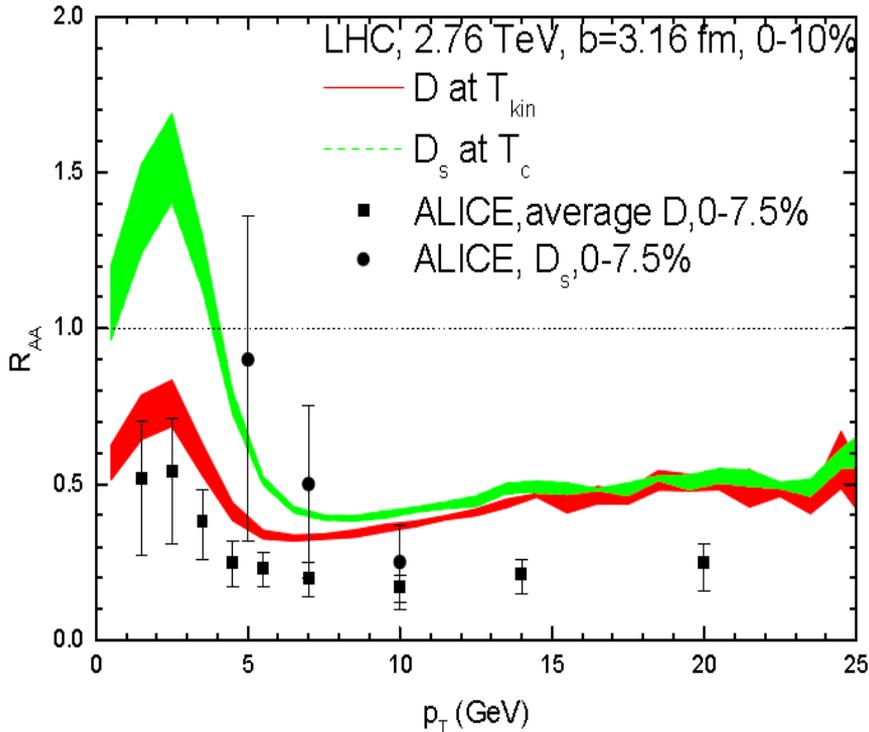
- ◆ **pronounced D/Ds flow-bump?!**
RRM = an extra interaction, driving D closer to equilibrium
 - ◆ **Ds $R_{AA} \sim 1.5-1.8$ at $p_T \sim 2$ GeV**
strong coupling c-QGP + coalescence + strangeness enhancement
(unique valence quark content csbar)
 - ◆ **Ds freezeout at T_c , D at T_{kin}**
D vs Ds v_2 : quantitative measure of charm interaction in hadronic phase
- ➔ a unique pattern of R_{AA} and v_2 of Ds vs D mesons emerges

3.3 Phenomenology: LHC D-meson



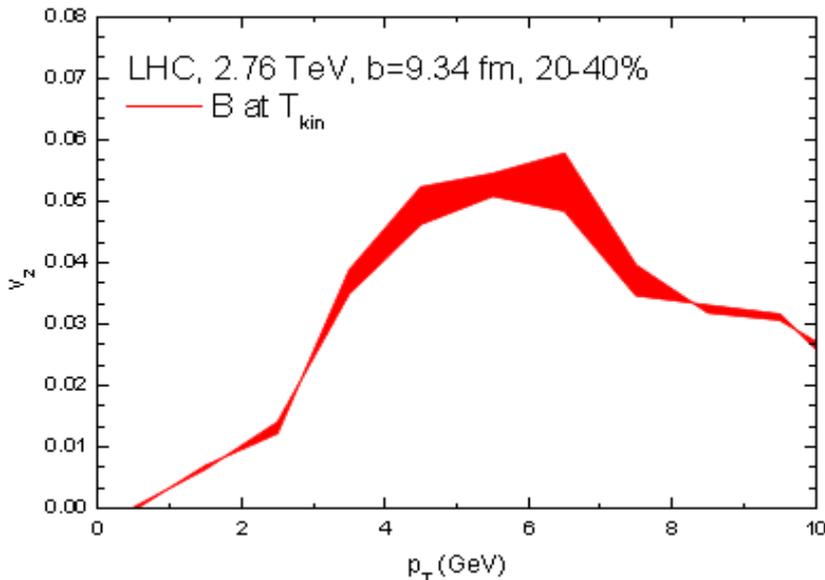
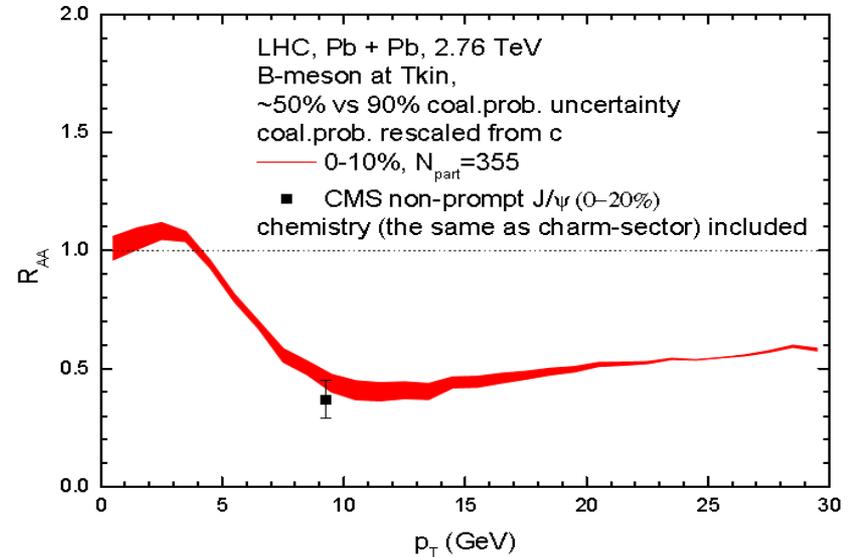
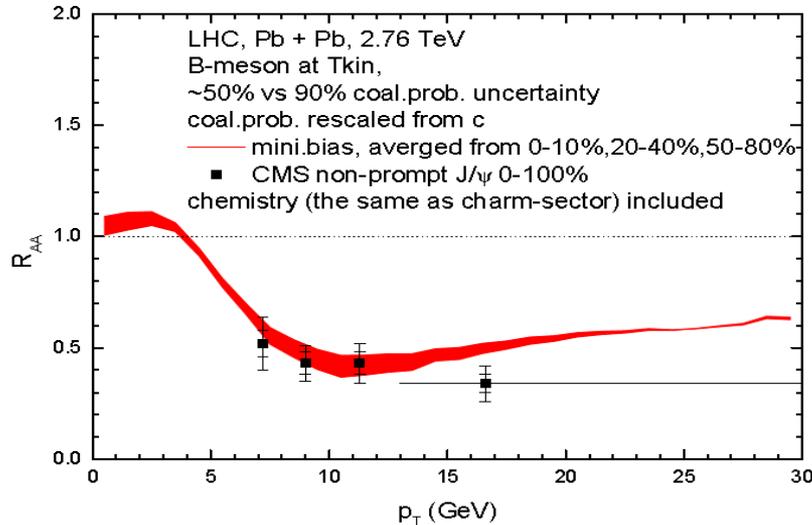
- ◆ R_{AA} : flow bump at low p_T , amplified by **coalescence**
 p_T -dependence shape OK; but ALICE data overpredicted, possibly indicating missing **radiative energy loss**
- ◆ v_2 : c-diffusion only accounts for ~50%
recombination and **hadronic phase diffusion** essential

3.4 Phenomenology: LHC D vs D_s , L_c



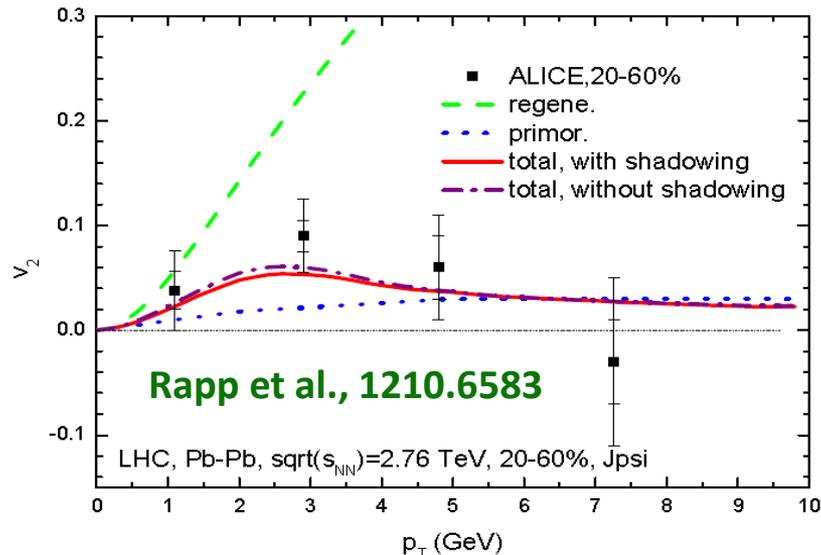
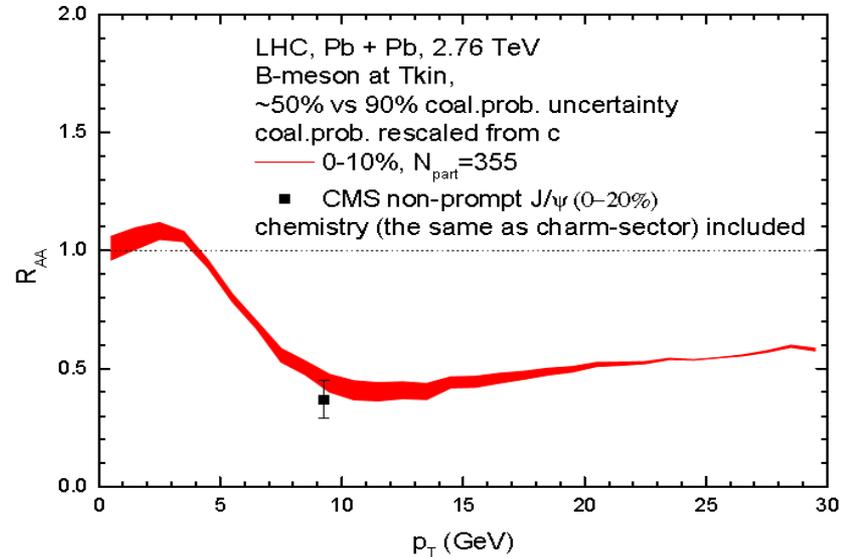
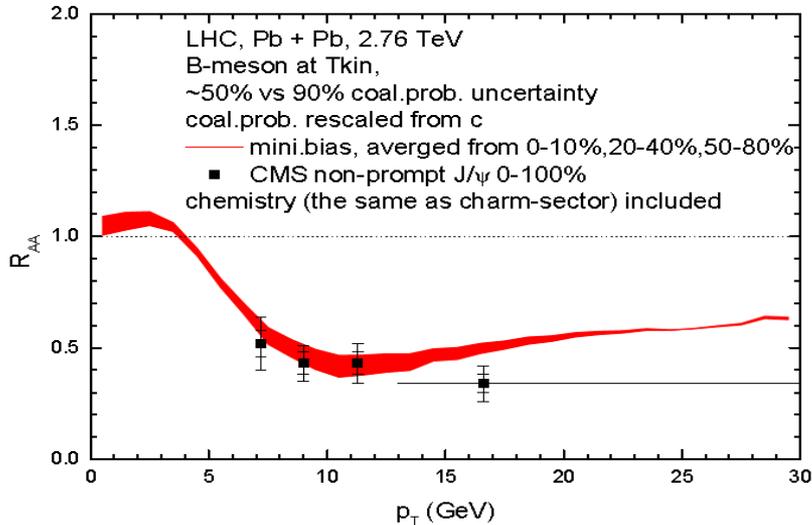
- ◆ D vs D_s R_{AA} : **low p_T , coalescence** enhances D_s production in a **strangeness-equilibrated, strongly-coupled** QGP medium
high p_T , D & D_s tend to the same universal fragmentation
- ◆ L_c/D ratio: **low p_T , heavier L_c subject to larger flow through coalescence** with two light quarks \rightarrow “dip” & “bump”
high p_T , tend to the pp ratio dictated by fragmentation

3.5 Phenomenology: LHC B-meson



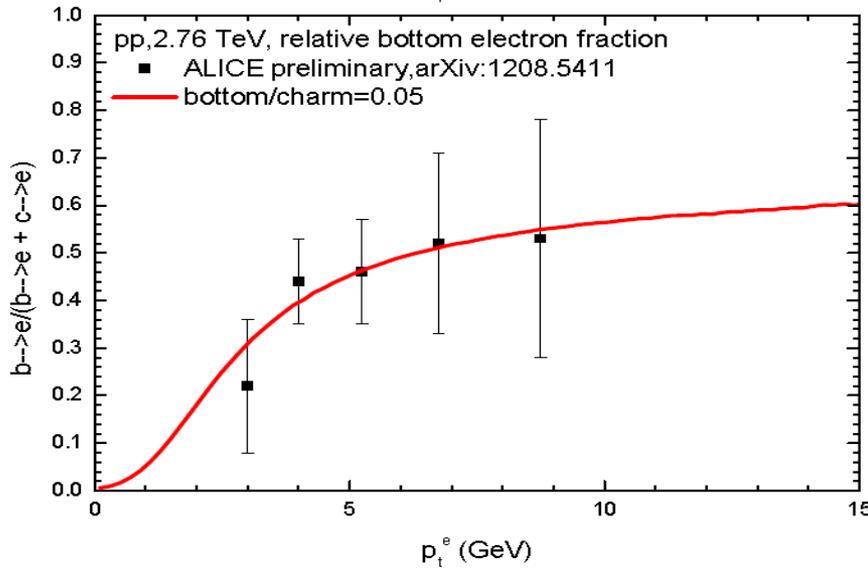
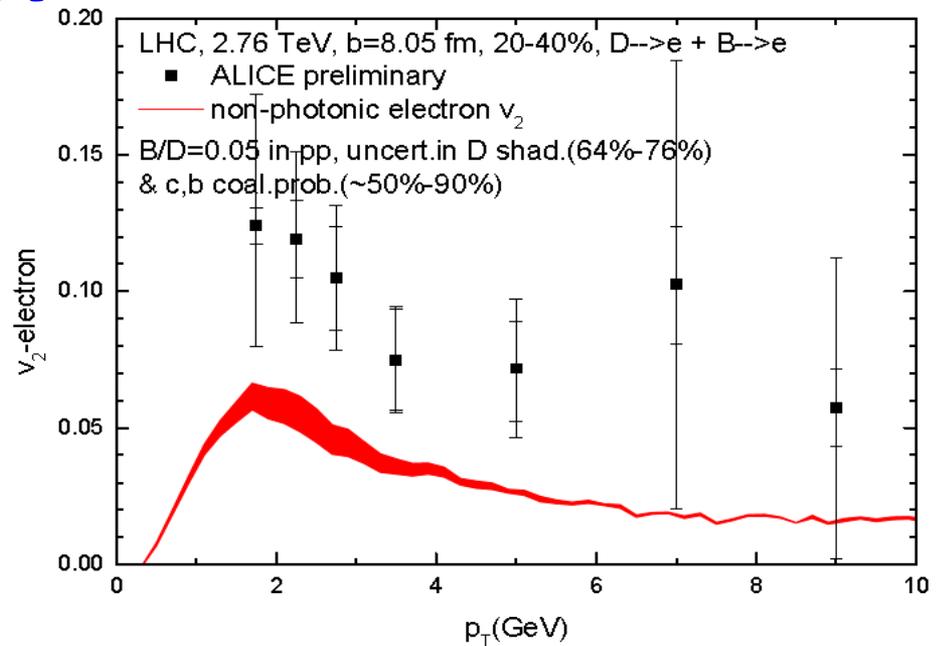
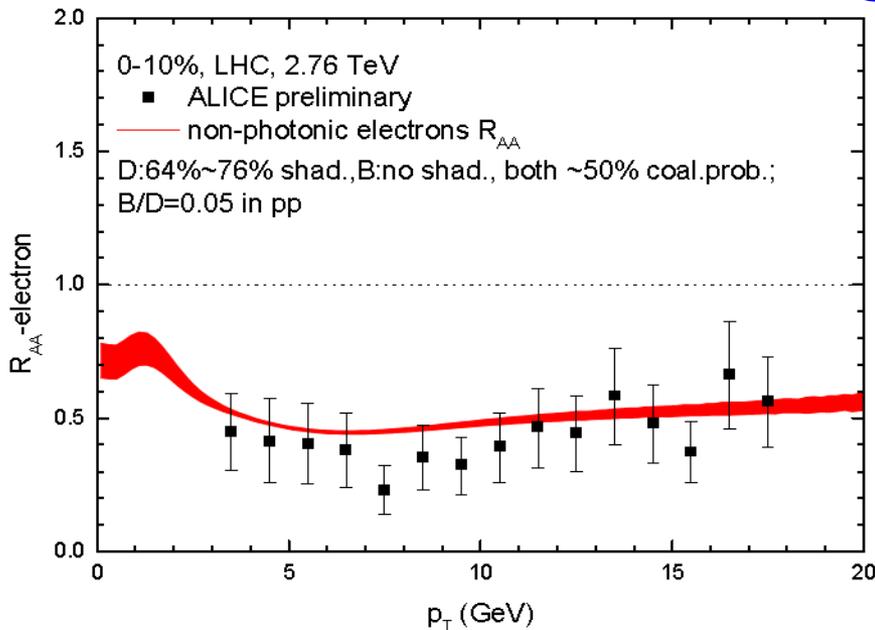
- ◆ R_{AA} : substantial suppression ($\sim 0.4-0.6$) at $p_T > 10$ GeV; consistent with CMS 0-10% (non-prompt J/ψ data point) or mini.bias
- ◆ Heavier B: elastic energy loss extends to larger p_T than in the D case
- ◆ v_2 : up to $\sim 5\%$, significant yet less collectivity than D mesons → implications for J/ψ v_2 ($B \rightarrow J/\psi + X$)

3.5 Phenomenology: LHC B-meson



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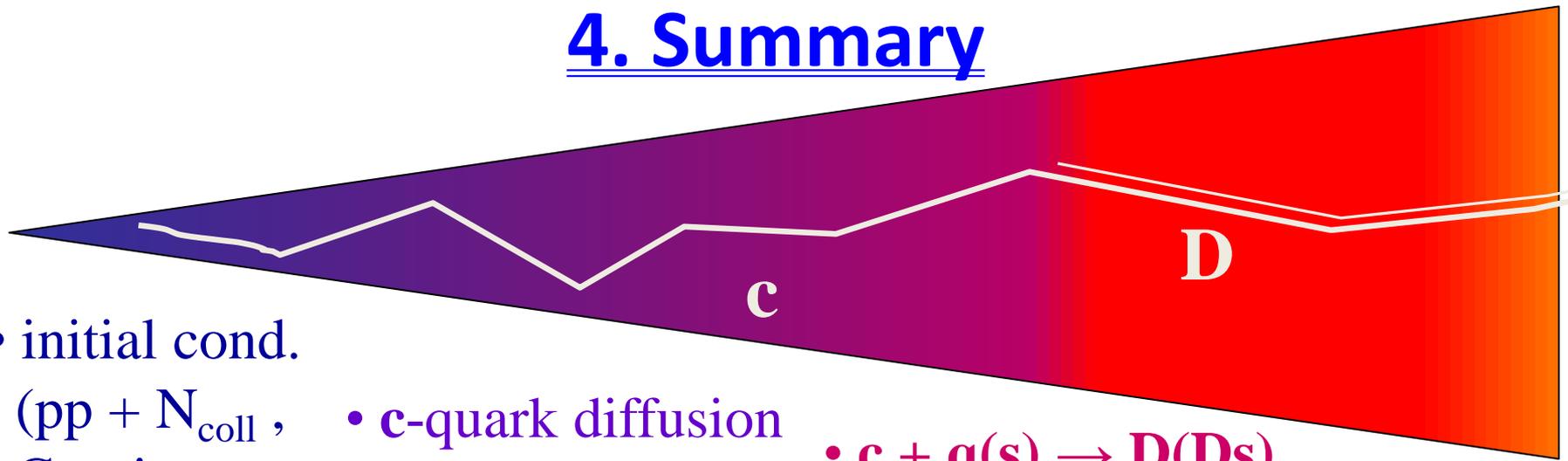
3.6 Phenomenology: LHC HF electrons



◆ R_{AA} : overpredicted in the D dominant region; fairly good in the B dominant region (elastic e-loss only)

◆ v_2 : underpredicted; radiative e-loss?

4. Summary



- initial cond.

(pp + N_{coll} ,
Cronin,
shadowing)

- **c**-quark diffusion
in QGP liquid
(**T**-matrix,
No K-factor)

- **c** + **q(s)** → **D(Ds)**
resonance
recombination;
Ds freezeout

- **D**-meson
diffusion in
hadron liquid

● Conceptual Consistency

- **diffusion** ↔ **hadronization**:

based on the same resonant interaction from T-matrix

- **diffusion** ↔ **bulk medium**:

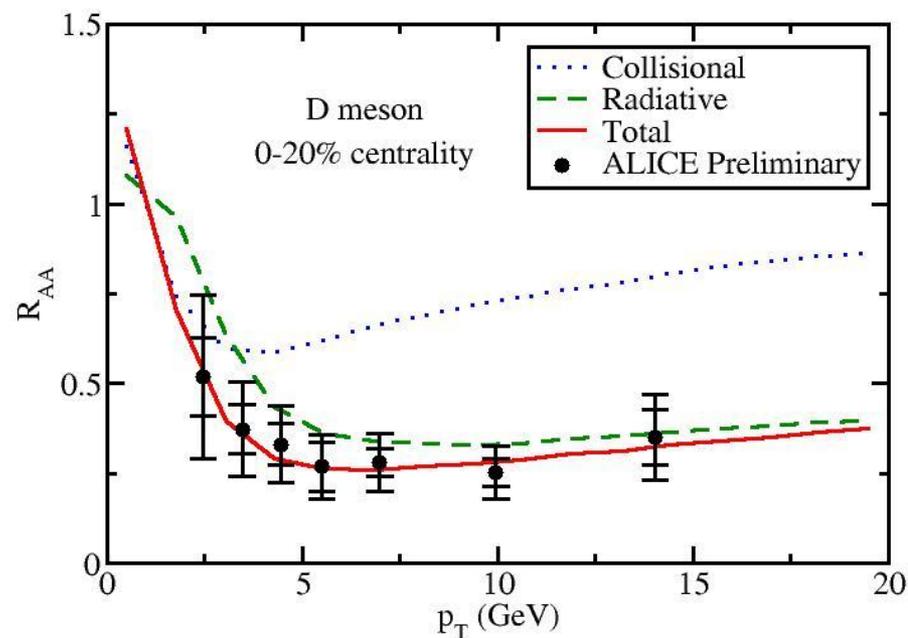
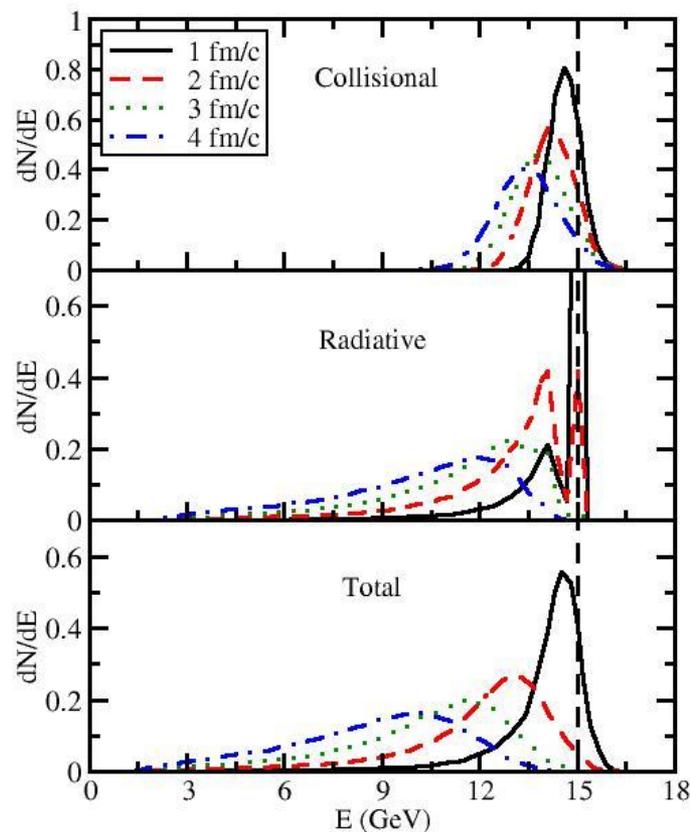
both based on strongly coupled QGP, **non-perturbative**

● Application: RHIC & LHC

dynamical charm flow features emerge

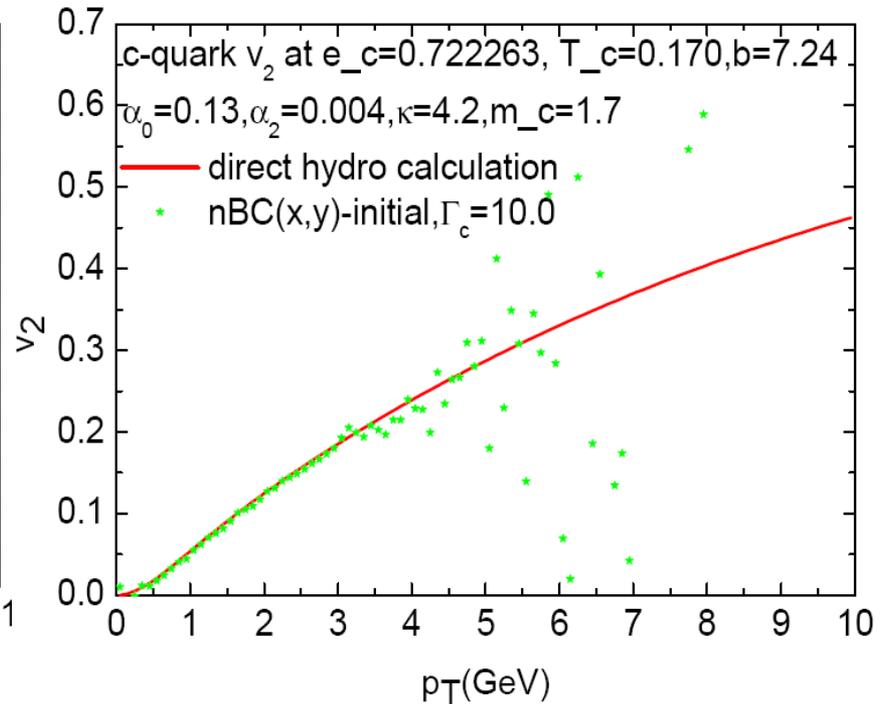
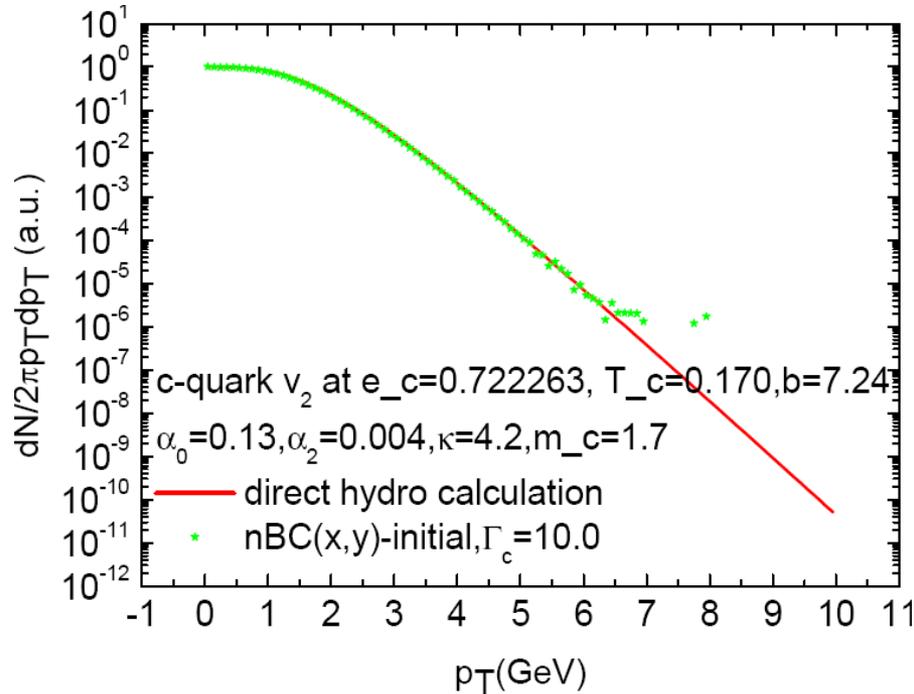
- Include radiative E loss of heavy quark by extending the Langevin equation

$$\frac{d\bar{p}}{dt} = -h_D(p)\bar{p} + \bar{\chi} + \bar{f}_g$$

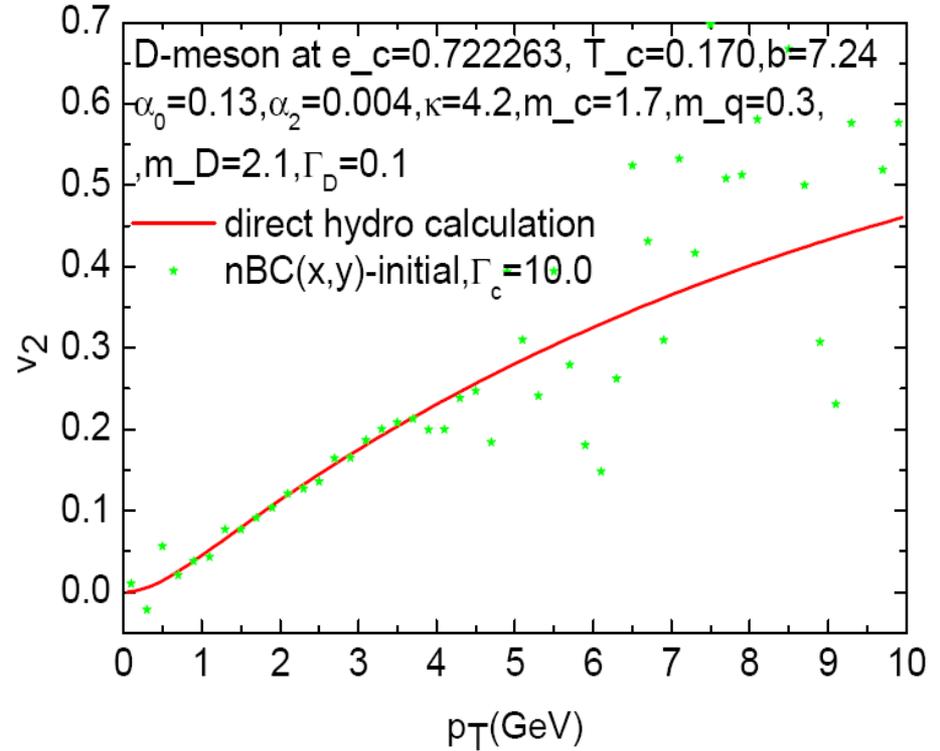
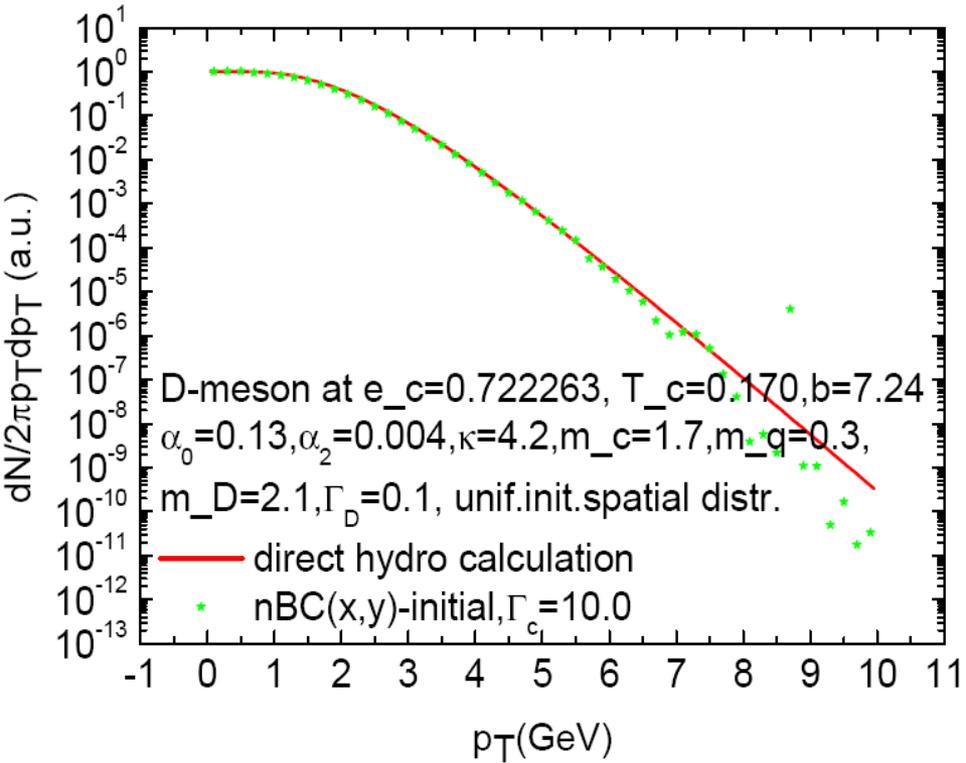


Respective effects of radiative & collisional E loss
Check effect on light flavors

Backup 1: charm quark Langevin diffusion equilibrium

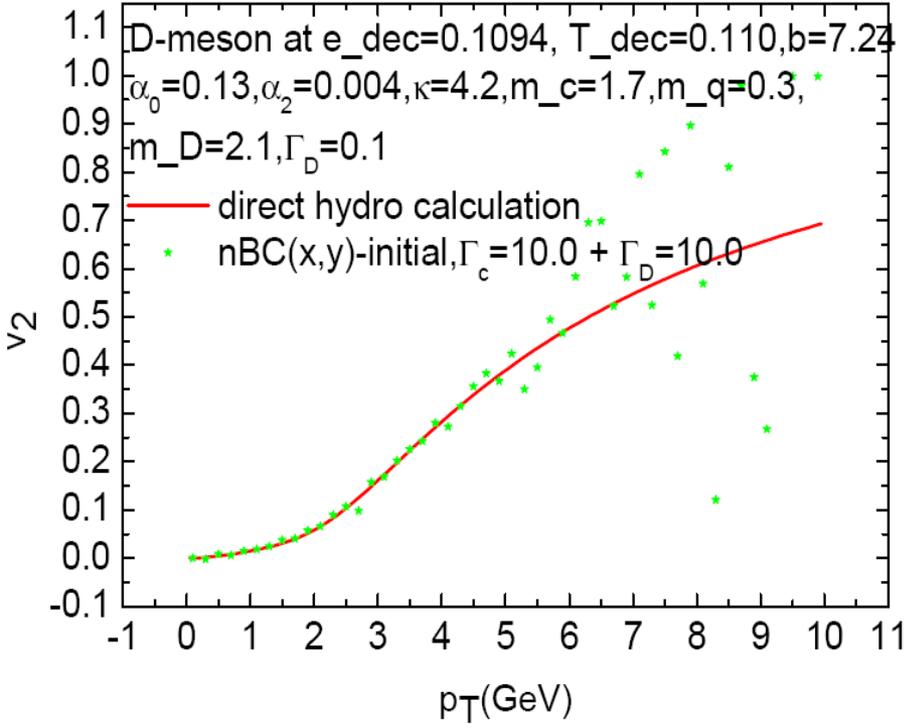
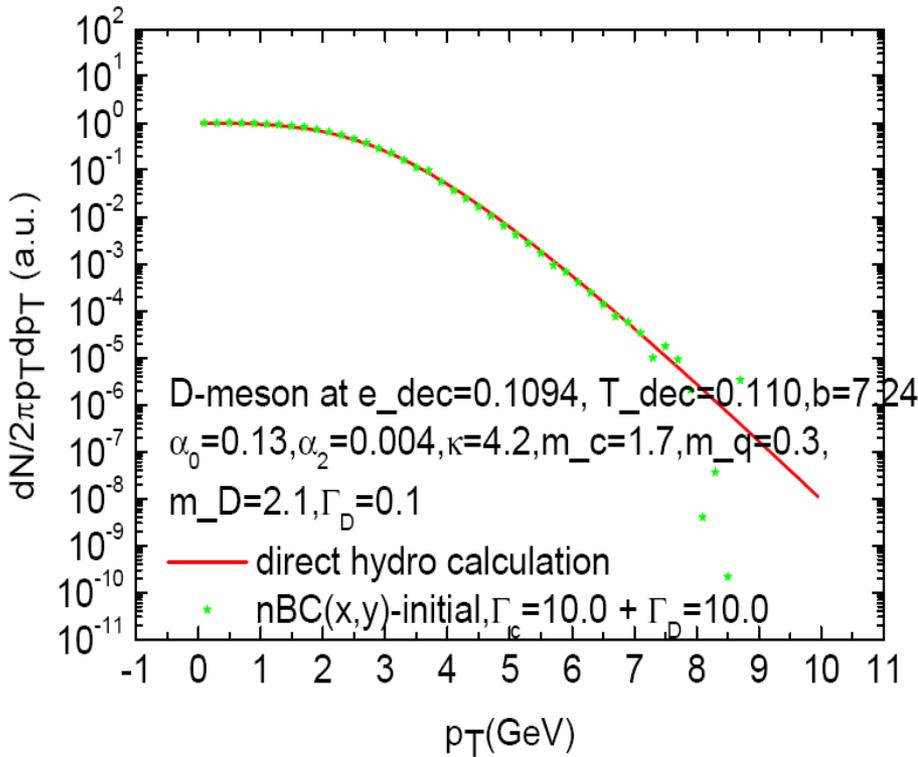


Backup 2: D-meson RRM equilibrium



Backup 3: D-meson hadronic phase

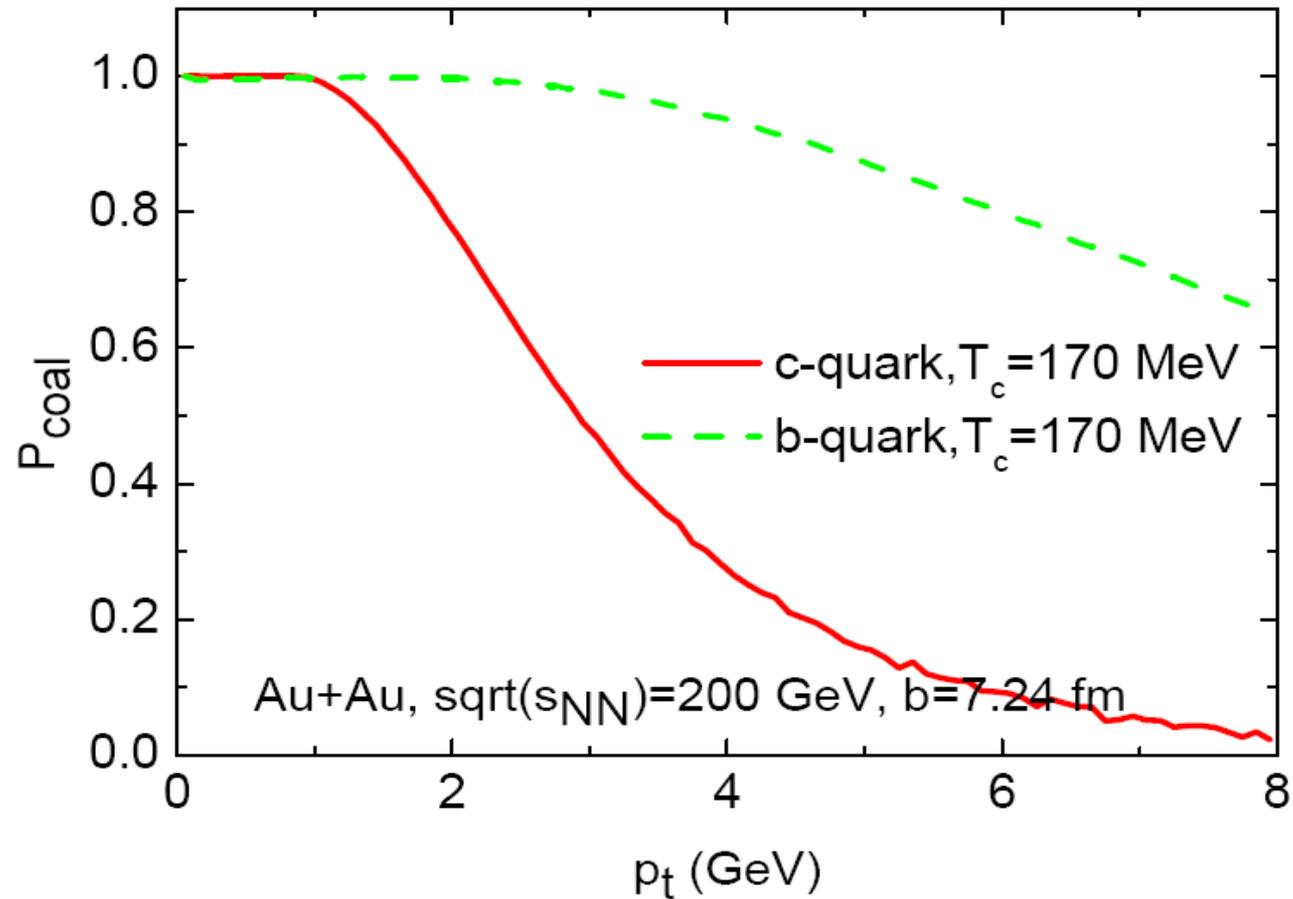
Langevin diffusion equilibrium



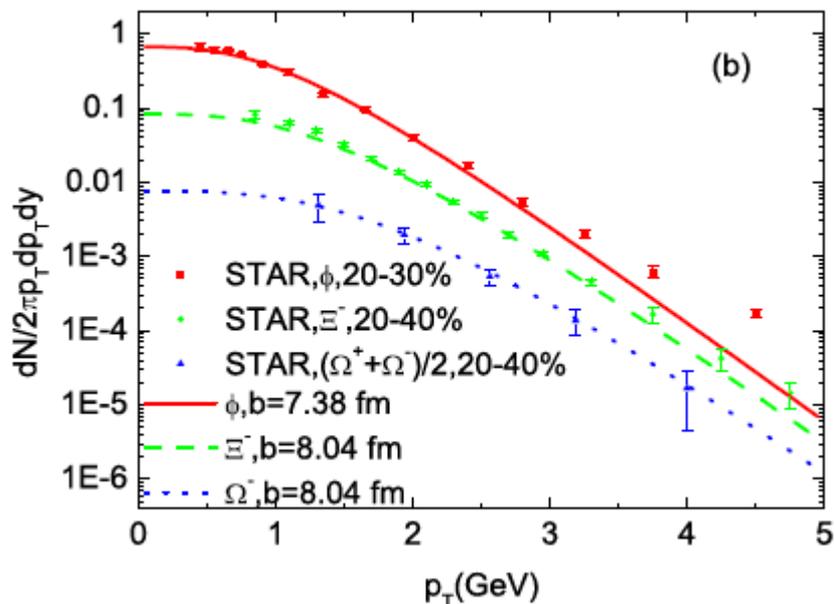
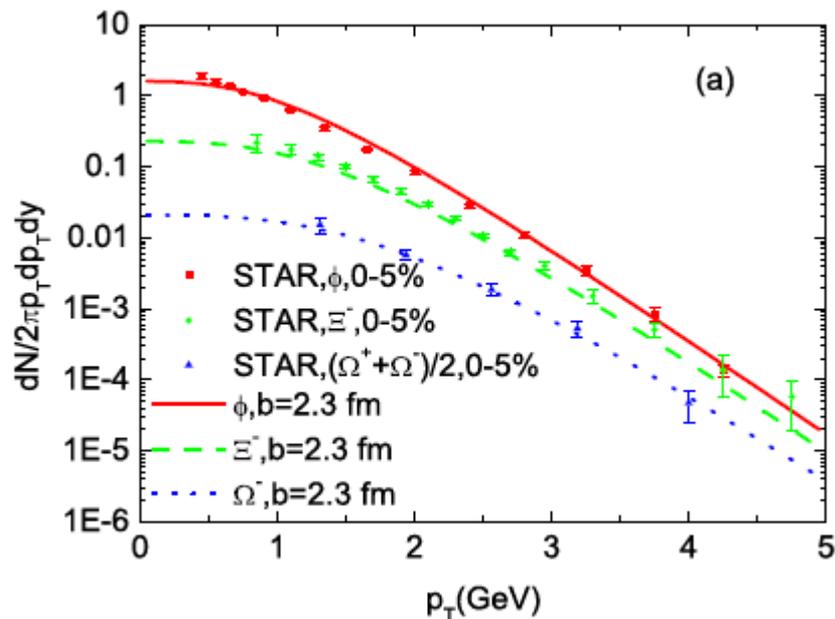
Backup 4: c/b coal.prob. based on scattering rate

- ◆ Aim: **formulate coal.prob. consistent with RRM**
- ◆ Quark scattering rate (vs thermal relaxation rate): $\gamma_Q = n \langle \sigma v_{rel} \rangle$
Breit-Wigner resonant cross section to reproduce color singlet contribution to relaxation rate \rightarrow scattering rate \rightarrow boosted to lab frame at the end of Langevin simulation: $\gamma_Q = \gamma_Q(p_t)$
- ◆ Charm quark scattering time: $\tau_Q = 1/\gamma_Q$. Within this time duration, we can form a D-meson/resonance through c-qbar resonant scattering (RRM). If the resonance formation time allowed by the system evolution (mixed phase duration) $\tau_{res} > \tau_Q$, $\rightarrow P_{coal}(p_t) = 1$; otherwise, $P_{coal}(p_t) = \tau_{res} \gamma_Q(p_t)$

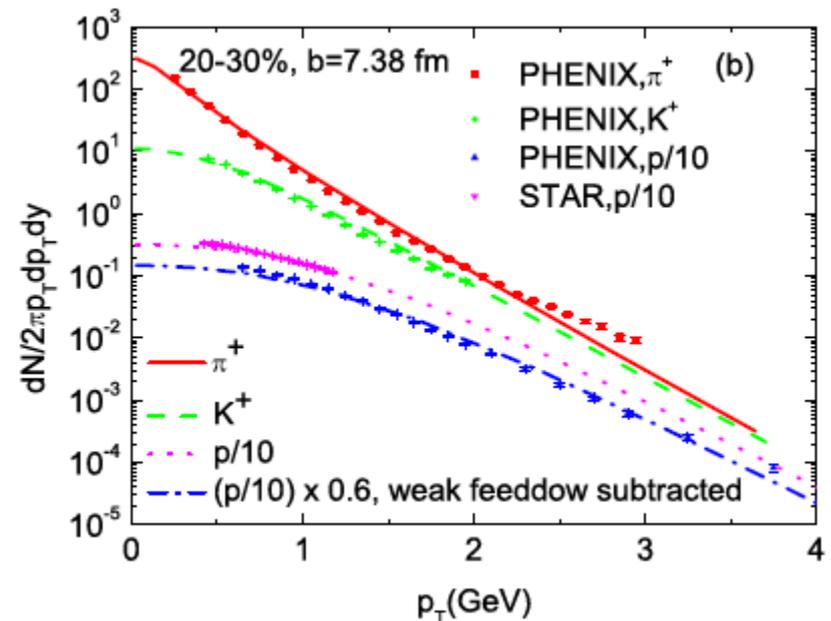
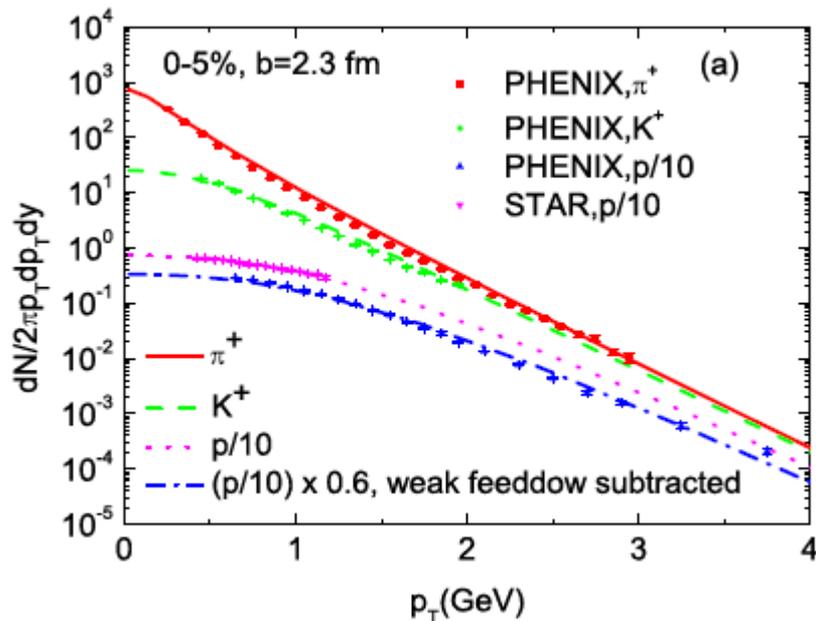
Backup 5: c/b coal.prob. based on scattering rate (continued)



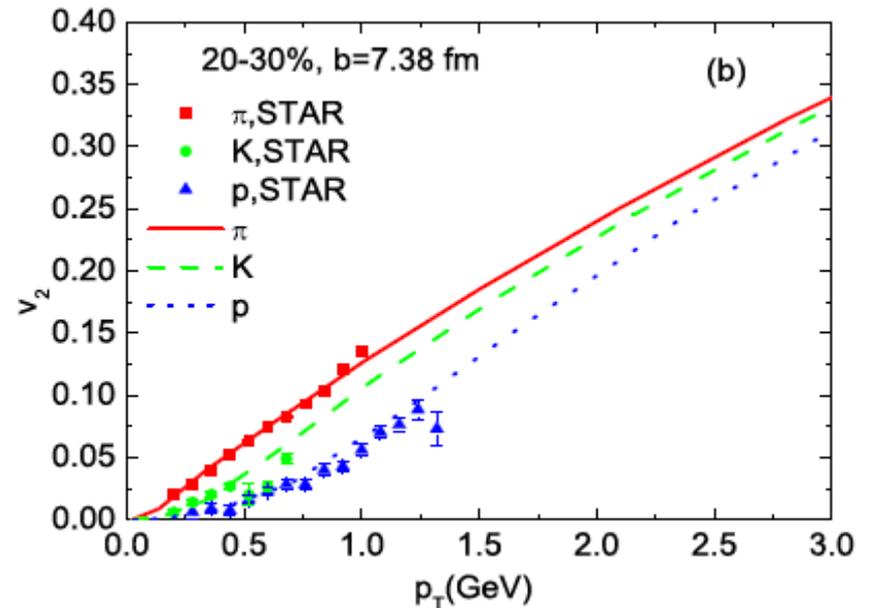
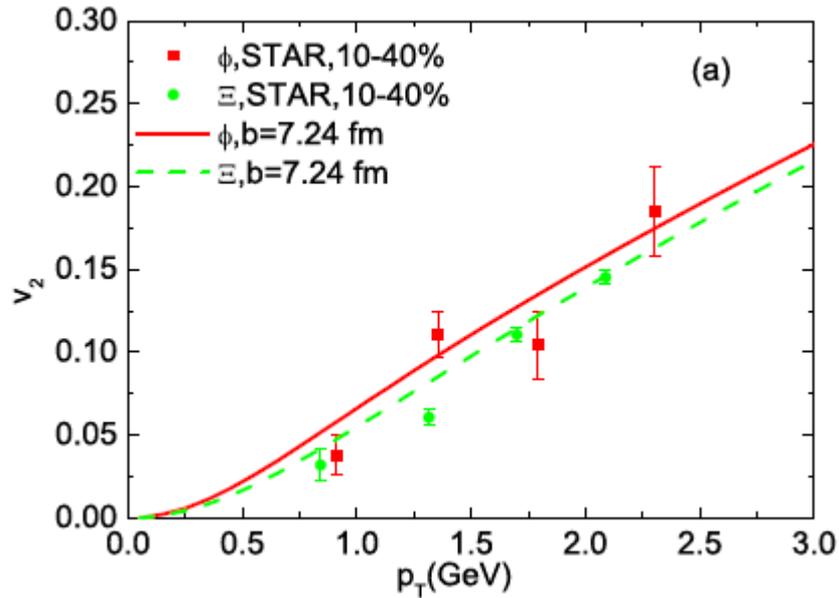
Backup 6: New hydro fits: multistrange particles' spectra



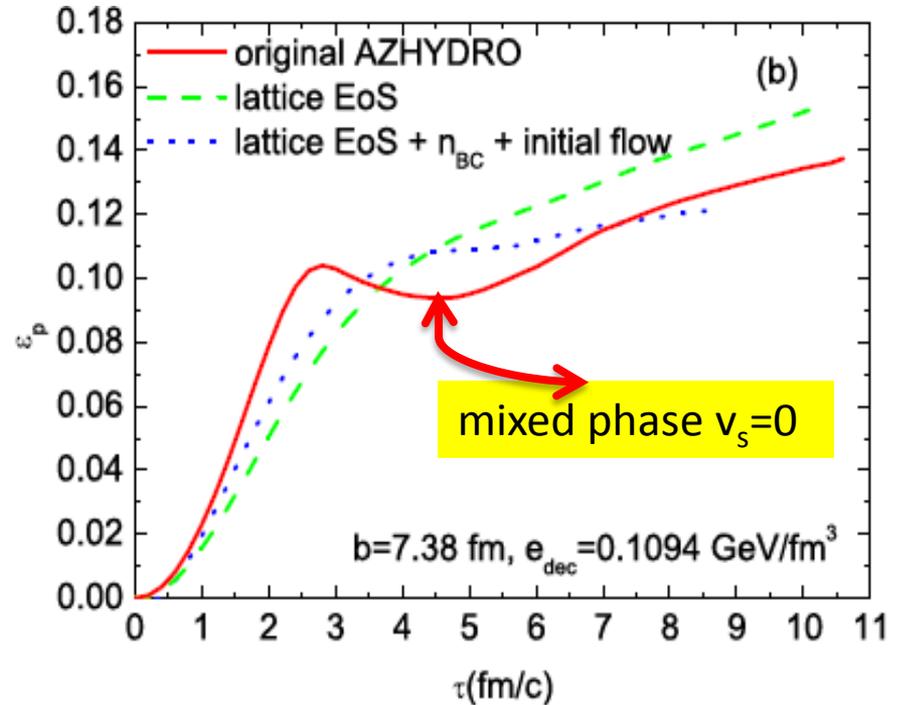
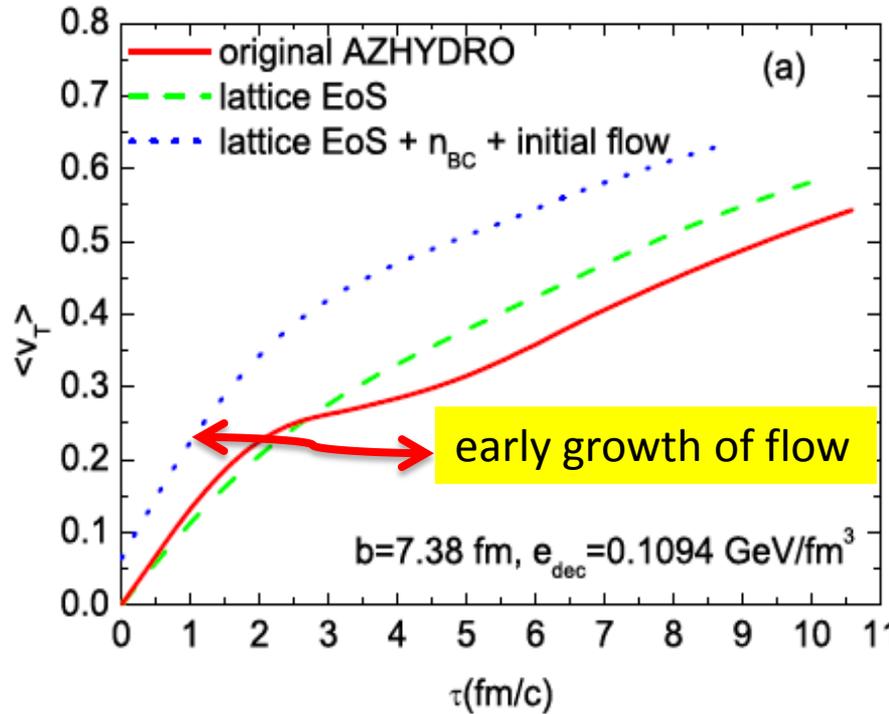
Backup 7: New hydro fits: bulk particles' spectra



Backup 8: New hydro fits: multistrange and bulk particles' v_2



Medium evolution: improved AZHYDRO

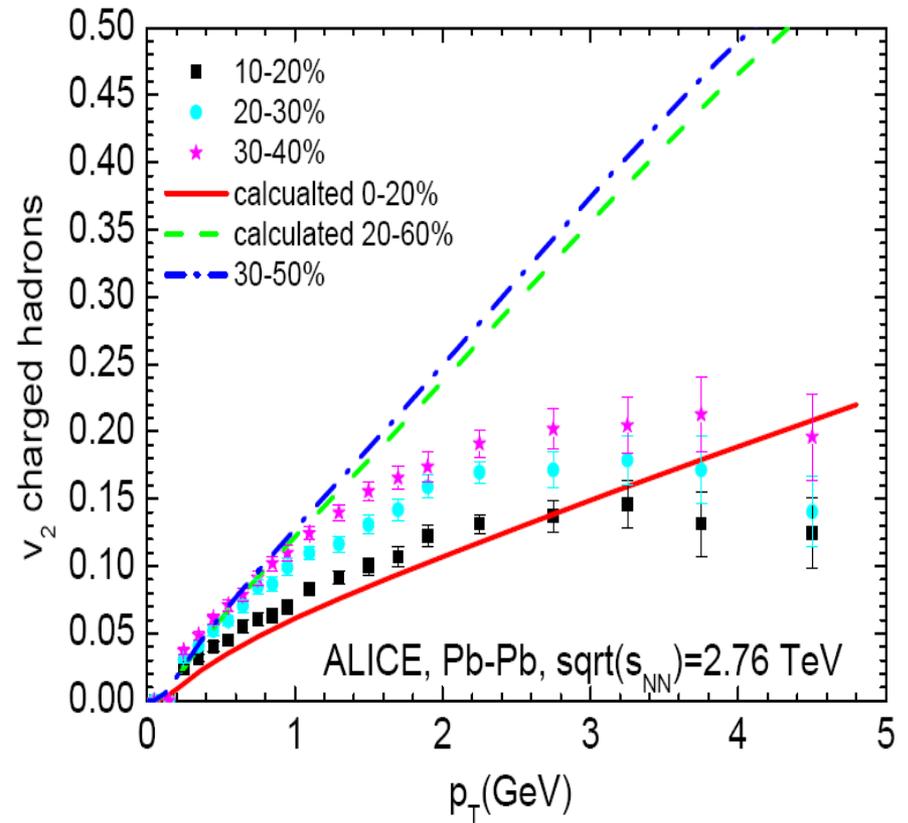
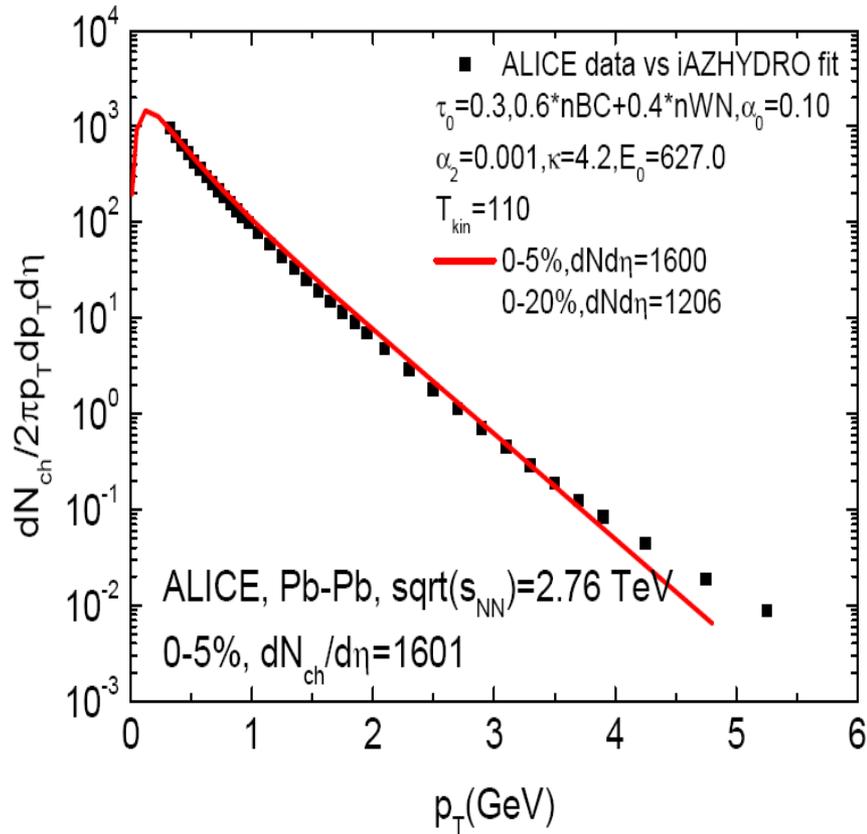


◆ lattice EoS + pre-equilibrium flow + compact initial density profile $s(x,y) \sim n_{BC}(x,y)$

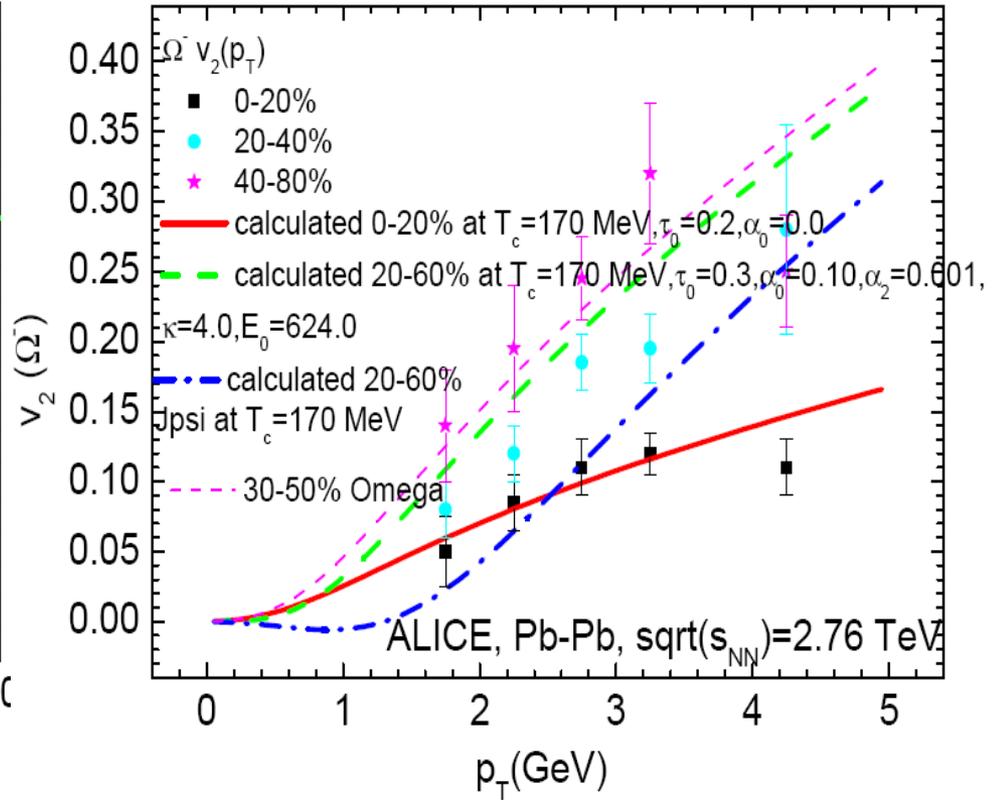
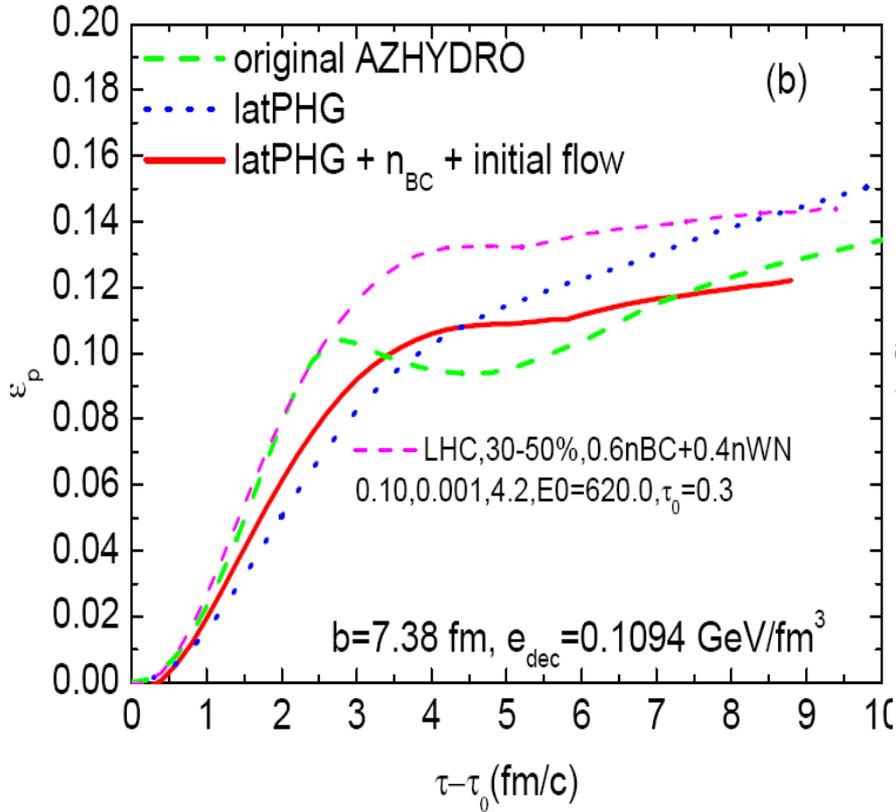
◆ multistrange hadrons ϕ, Ξ, Ω probably freeze out earlier STAR, PRC79,2009

◆ multi-strange particles' spectra and v_2 fitted at $T_{ch} = 160 \text{ MeV}$
 bulk particles' spectra and v_2 fitted at $T_{kin} = 110 \text{ MeV}$
 M. He, R.J.Fries, R. Rapp, in preparation

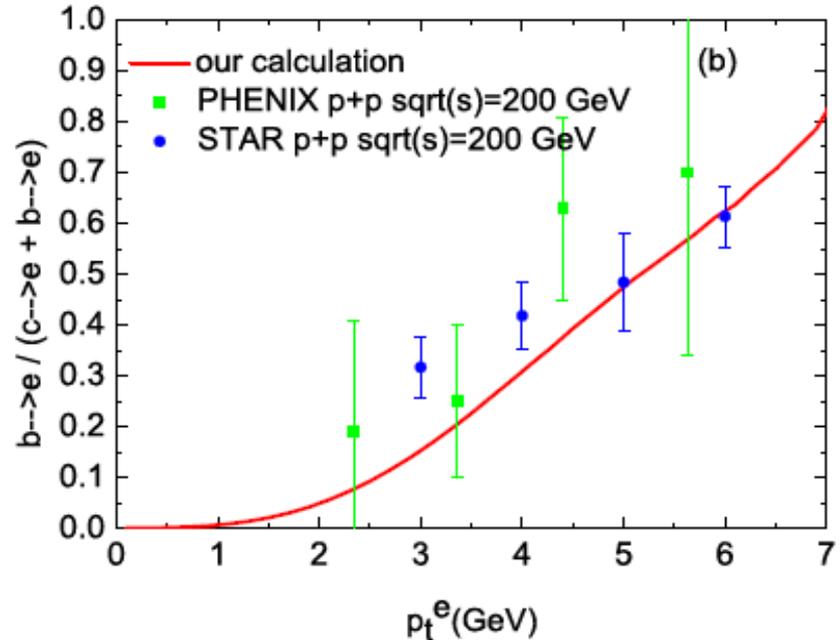
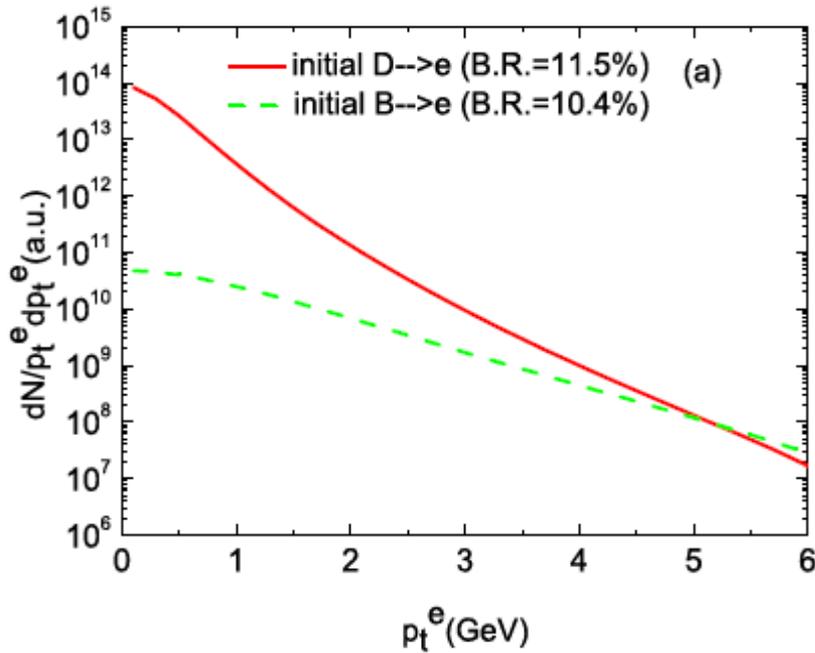
LHC: Hydro tuning (1)



LHC: Hydro tuning (2)



HQ initial distribution



◆ initial p_t spectrum: PYTHIA parametrization

→ $B \rightarrow e$ starts to dominate over $D \rightarrow e$ at $p_t \sim 5$ GeV,

$$\frac{d^2 N_c}{dp_T^2} = C \frac{(p_T + A)^2}{(1 + p_T/B)^\alpha}$$

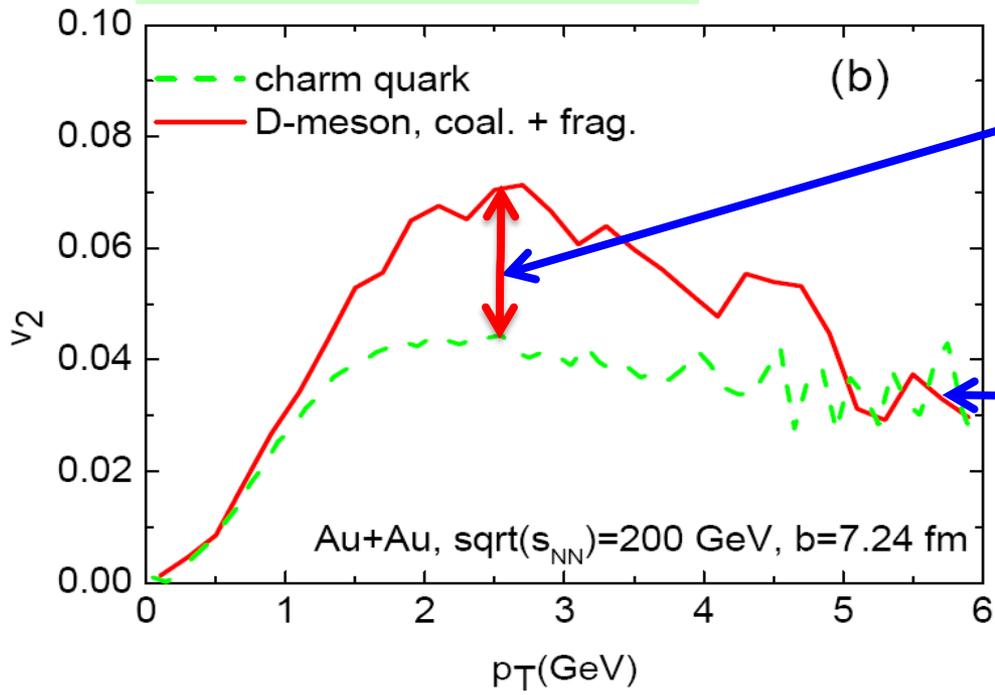
$$\sigma_{b\bar{b}}/\sigma_{c\bar{c}} = 4.9 \times 10^{-3}$$

◆ Initial spatial distribution: Glauber binary collision density $n_{BC}(x,y)$

OLD Hadronization: coal. vs frag.

- ◆ coal. vs frag. :relatively normalized with the calculated coal. prob.

$$\frac{dN_D^{total}}{dyd^2 p_T} = \frac{dN_D^{coal}}{dyd^2 p_T} + \frac{dN_D^{frag}}{dyd^2 p_T}$$



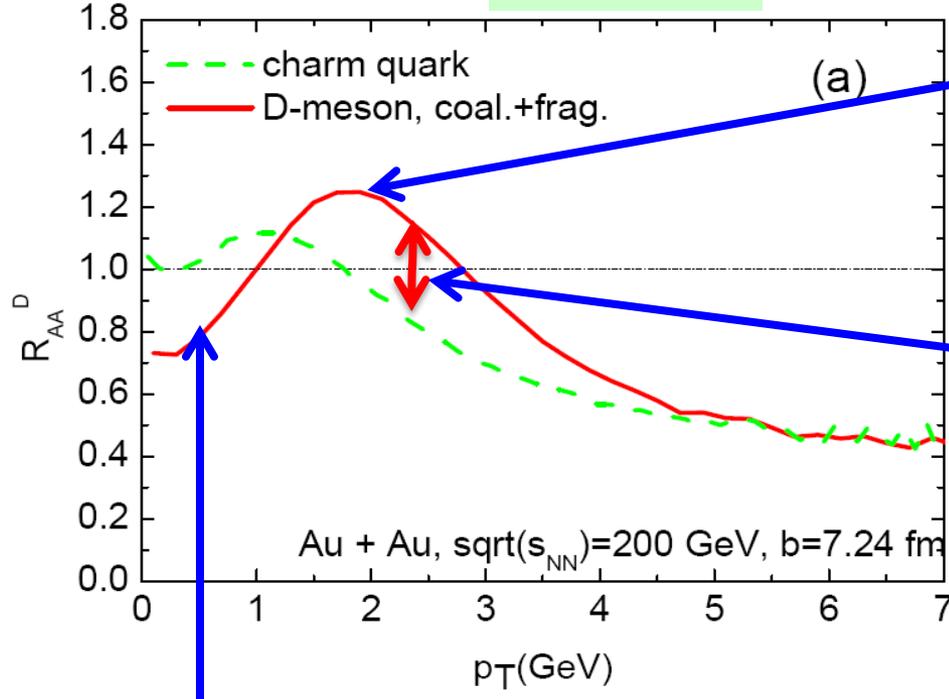
◆ coalescence: adds v_2 from the light quarks to D meson

◆ at higher p_T , coal. yields to frag.: preserves the HQ v_2 from $c \rightarrow D$

- ◆ **space-momentum correlation** built up via Langevin + hydro for HQ & q from hydro environment fully implemented in RRM
- ◆ RRM admits equilibrium mapping between quark and meson distributions, thus able to capture the remarkable flow effect via heavy-light coalescence

OLD Hadronization: coal. vs frag.

- ◆ charm quark coal. prob. based on scattering rate: $P_{coal}(p_t) = \tau_{res} \gamma_Q(p_t)$
- ◆ supplemented by $D(z) = \delta(z-1)$ fragmentation



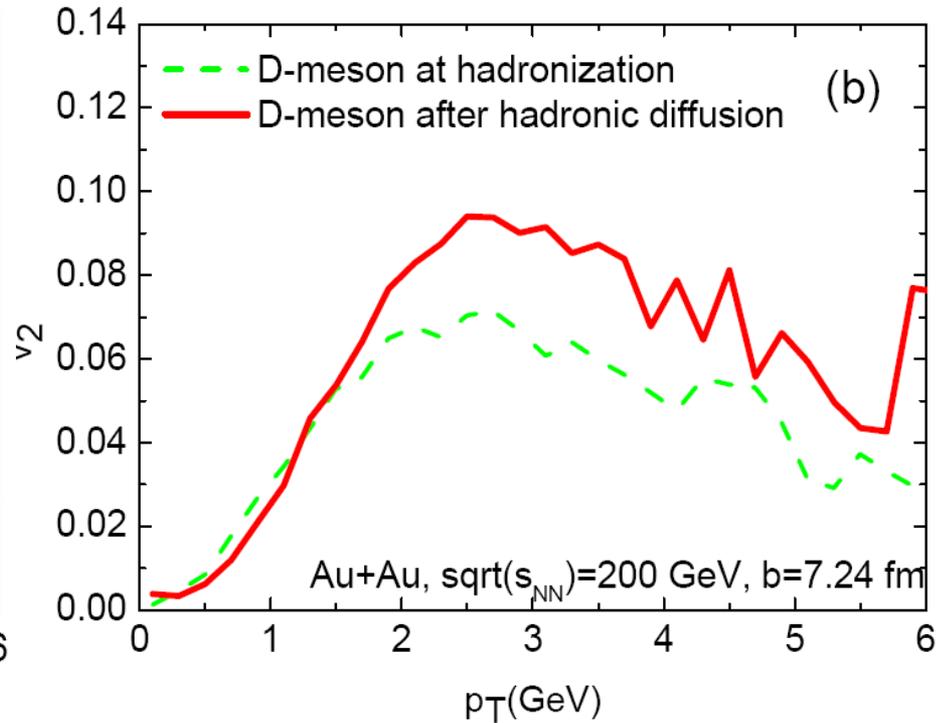
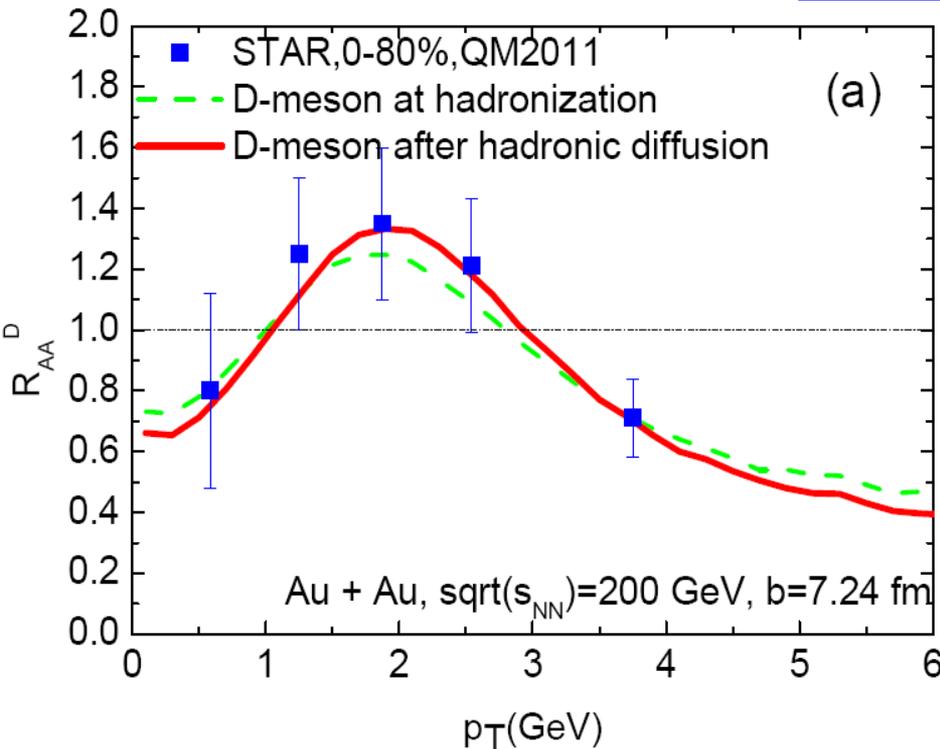
◆ **flow bump** more prominent from c to D & shifted to higher p_T

◆ At $p_T \sim 1.5-4.5$ GeV, coalescence adds momentum to D, R_{AA} increases from c to D

◆ At low p_T , D- R_{AA} gets a larger dip, than charm; **flow depletion** on D, captured by **c-q RRM**

Coalescence acts as an **extra interaction**, driving D-spectrum closer to **equilibrium**

OLD D/B hadronic phase Langevin diffusion



◆ flow bump somewhat shifted

◆ spectrum quenching continues, but largely counteracted by the hardening effect of **large hadronic flow** → R_{AA} not change much

◆ v_2 amplified by ~30%

◆ though bulk v_2 does not quite grow in hadronic phase, D-meson continues to **thermalize** and **pick up v_2** from the medium

